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FABRICATION AND TESTING OF MAINTENANCE EQUIPMENT USED FOR PAVEMENT SURFACE REPAIRS

Final Report

SHRP H-107A

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2.5.1.1 - Component Description

The routing component consists of a commercial impact cutting wheel mounted in a frame supported on casters. It is a modular unit that can be attached to the longitudinal or general crack sealing machines. The weight of the router unit is supported entirely by its wheels, and the wheeled frame is designed to resist all forces that act to upset the cart during operation, including forces from the RPS to which it is attached. The cutting wheel is driven by a hydraulic motor with the fluid flow lines running from the cart to the power unit on the truck bed. Detail drawings of the router are located in Appendix E.1. Figure 2.5.1 depicts the basic components which are described in the following paragraphs. Note that the item numbers in this figure correspond with those of the router assembly drawing SHRP(APS)RM-A100 in Appendix E.1. Photos of the actual fabricated unit can be seen in Figures 2.5.2 and 2.5.3.

The router cutting wheel (item 14) is a commercial unit removed from the manually operated router described above. The cutting wheel holds six rows of cutters and is designed to run at 2000 RPM. The cutters have a diameter of 4.75 inches and the total effective cutting diameter of the wheel is 15 inches. The maximum cutting width of this particular wheel is 2.25 inches, limited by its cutting wheel design.

The router cutting wheel and hydraulic motor (item 8) are mounted on bearings (item 12) attached to the cutter frame (item 13) which is hinged at the forward end. This allows the cutter to be extended into the road and retracted. The range of motion in the present design allows for a cutting depth of up to 0.85 inches and a retraction of 1 inch. An electric linear drive actuator (items 3 & 7) is used to extend and retract the cutting wheel. The cutter frame rotates about the C-channel pin (item 11) which is bolted to the inner frame (item 6). The inner frame serves as the shroud and the attachment point for the linear drive and linkage which extends and retracts the cutting wheel. This assembly is a very compact, self-contained mechanism which is then bolted to the wheel support frame (item 2).

Figure 2.5.1 - **Description of router assembly, items numbers are circled.**

Figure 2.5.2 - Photo of the fabricated router unit. For illustration purposes the top cover was removed.

The wheel support frame is mounted on four casters (item 1) and supports the weight and cutting forces of the complete router. It also provides the interface to the RPS machines. It is designed to sit inside the longitudinal machine cart and in this configuration, the casters of the longitudinal machine are removed and the weight of the longitudinal machine cart and the other APS components is carried by the wheel support frame of the router. An attachment point on the top of the wheel support frame provides the interface for the general machine robot.. The connection will include a constant velocity joint to allow the router to gimbal over the uneven road surface while still being able to transfer rotation from the robot's end effector joint. The general machine router joint will also be fitted with a vertical sliding shaft to maintain contact with the road surface without having to change the robots vertical position.

The router's internal linear drive motor has a range of 4 inches and extends and retracts the cutting wheel by rotating two of the links as part of a four bar linkage, as shown in Figure 2.5.4. It acts at the upper and lower link capture (item 5) which is a clevis that shares a pin with two links on the actuator side of the assembly. The two upper links (item 4) are attached to a common shaft at the upper link pin (item 9) and move as a single member acting on the two separate lower links (item 15). The linkage is designed so that at full extension of the actuator, the upper and lower links are in line with each other and the loads transmitted from the router cutting wheel to the inner frame have no component in the direction of the actuator. In order to provide for cutting at different depths, the attachment of the lower link hinge point to the cutter frame is adjusted at the lower link pin block (item 10). The adjustment is set prior to operation of the router. The linkage is designed to retract the cutting wheel 1 inch above the surface of the road. Through the use of a linkage that is self-locking, the actuator will only be subjected to routing impact forces while it is extending the

Figure 2.5.3 - The router unit underside. Note the compact hydraulic motor.

cutting wheel into the road. The nominal cutting depth that the router can be set for is 0.1 to 0.85 inches. This accommodates the 0.75 inch cut being evaluated in SHRP H-106.

The router has a debris shroud to facilitate the removal of the asphalt cuttings dislodged during the pavement routing operation. The debris shroud consists of a stainless steel brush strip attached to a removable metal strip that is bolted to the bottom of the router shroud assembly. It includes a deflector plate and vacuum tube forward of the cutting wheel which directs the debris to the vertical tube attached to the vacuum line of the debris removal system. The debris shroud provides a partial vacuum seal with the road surface and will act to retain the debris ejected by the cutting wheel. The debris is emitted forward by the action of the cutting wheel so that the flow of the air will be directed by the vacuum in this same direction and exit forward through a transition from a rectangular cross section into a 3 inch diameter tube.

The hydraulic motor is keyed directly into the end of the shaft that drives the cutting wheel. The displacement of the motor is 1.95 in^3/rev which is designed to have an output of about 17 HP at 2000 RPM. The power for the router is being provided by one of the outlets of the mobile hydraulic power unit which is mounted on the truck platform. Operation is achieved by powering the motor with the router retracted, then extending the cutting wheel into the ground to full extension while stationary. Once extended the router is moved forward to cut the channel. The router can be operated by either the LPS or RPS by simply moving the hydraulic hoses on the truck.

Operation of the router has been simplified to a start and stop signal that can be sent through the ICU interface screen or manually with buttons on the external control box. When the routing operation is started, the control circuit energizes the hydraulic solenoid and delays the lowering of the cutter until the hydraulic motor is up to full speed. Sending the stop signal to the control circuit will retract the cutters before stopping the cutter rotation, protecting the cutting blades from damage. For safety reasons, the router control circuit is powered by the twelve volt DC current of the truck's electrical system. Thus, if the main AC generator failed during the routing operation, the router could still be correctly shutdown. The hydraulic power unit is diesel engine driven and will continue to run during a power failure.

2.5.1.2 - Principles of Operation

The router, one of the APS components, is used to prepare cracks by cutting a channel along the crack in a profile that allows for increased penetration and adhesion of the sealant. The router was developed to accommodate the unique requirements imposed by the crack sealing machine. The design uses an existing impact router cutting wheel installed in a configuration that will follow random cracks with the general purpose RPS or the nearly linear cracks with the longitudinal RPS. It is hydraulically powered, allowing it to be operated with a remote power supply. As a result, its size and weight are minimized to best accommodate its use with the RPS systems. In addition, the design allows for cutting at the increased speeds necessary for the automated crack sealing applications. The impact cutter design allows for variations in cutting depth and width which can be adjusted by placing the individual cutting wheels in various configurations. Adding cutters and increasing the rotational speed of the cutting wheel assembly also allows for operation at higher road speeds. The router component is a modular unit that will operate in both systems with minor modifications.

The basic principles of impact router operation have been verified on a manually operated commercial routing unit. The operator, while walking backwards and pulling the machine, guides the unit by observing the cutting wheel as it follows the crack. Debris is thrown in the direction away from the operator. This mode of cutting runs the cutter wheel in a "down-milling" cut direction (see Figure 2.5.5). Testing showed that the router tended to pull itself up out of the road bed when operated at higher surface speeds. By pushing the router, which results in a conventional "up-milling" cut (see Figure 2.5.5), the operation of the router is considerably smoother. Greater force is required to push the unit since the resulting cutting force acts in the direction opposite the direction of travel. However, a significant advantage is that the routing machine does not pull itself out of the roadway when "up-milling". Test results determined that operating the router in the conventional "up-milling" mode was the most efficient and would be used for the APS router component. This option is not possible with the manually guided machine since the debris would be thrown toward the operator.

Figure 2.5.4 - Router cutting wheel extension and retraction.

Figure 2.5.5 - Description of router cutting wheel operation.

2.5.2 - Heating/Cleaning/Debris Removal

2.5.2.1 - Component Selection

The main component in the heating, cleaning and debris removal (HCD) subsystem is the burner. Four liquid propane heating systems from major burner manufacturing companies were identified using the computational models developed earlier and appeared to closely meet the overall design criteria. However, two were logically concluded to best do so: the previously investigated Sur-Lite burner and the Eclipse Thermal Blast Heater. As mentioned in previous reports, Sur-Lite's modular design affords the possibility of incorporating a larger blower. However, the recently investigated Eclipse Thermal Blast Heater is limited to a maximum 400 SCFM of air flow. Yet, this burner is built for high pressure operation, up to 50 PSI, and has been designed around the operating envelope specific to this application. The Eclipse burner also ejects its hot exhaust via a 4" diameter duct as opposed to Sur-Lite's 6" exit. This means that in order to reduce the exhaust area at the nozzle to increase flow velocity, the Sur-Lite system would experience a much greater pressure drop and generally be more bulky. Also, the Thermal Blast Heater is designed specifically for remote blower placement. In the case of the Sur-Lite burner, less routine modifications would be necessary. Therefore, it seemed reasonable to conclude that if the heat output from the Eclipse burner is not significantly limited by the 400 SCFM maximum flow and the burner can heat the crack to 250°F at a relative speed of 2 MPH, then it should be selected as the preferred method. A simulation using the convective model was run and indeed, a sufficient surface temperature of 260°F was achieved (see Figure 2.5.6 below). Thus, the Eclipse burner was chosen for integration with the automated crack sealing vehicle. Selection of the flame safeguard and fuel train was fairly straight forward since it is made of components commonly available through most burner manufacturing companies. For convenience, a local vendor, Control Technology Specialists, was chosen to provide this portion of the HCD system and to help install and fine tune the heating system as needed.

More straight forward were the component selection choices for the blower and debris separator. The Paxton CB-87 comes as a complete package as opposed to most other hydraulic blower and therefore, best meets project goals in terms of off-the-shelf reliability. EG & G Rotron provides a debris separator that is able to be easily emptied using a standard 55 gallon drum mounted on casters. Both of these units were therefore purchased for use with the heating system outlined above.

2.5.2.2 - System Description

The automated pavement crack heating, cleaning, and debris removal (HCD) system designed and purchased primarily consists of an EG & G Rotron debris separator, model IVM2000PF (approximately the size of 2 - 55 gallon drums stacked vertically), a 5 PSI, 400 SCFM hydraulically powered centrifugal blower, Paxton Centrifugal Blowers model CB-87, a 692,000 BTU/hr Eclipse Thermal Blast Heater, and an infrared pyrometer, Raytek model ET3LT, which measures crack temperature and thereby modulates fuel flow to the burner. Overseeing safe operation of the burner is a standard flame safeguard control panel built by Control Technology Specialists. It features additional control panel functions for diverter valve actuation (to ensure safe idle operation), CLEAN ONLY operation (no heat), and a PID controller to interface with the pyrometer.

The debris removal portion of this system consists of a debris shroud mounted to the router casing, the EG &G Rotron debris separator unit and waste container located on the truck bed, and two (2) 3" diameter flexible hoses. The Paxton blower provides vacuum air to the debris shroud and separator unit and the waste container houses all collected debris for later disposal. Both the blower and burner units are to be located on the truck in a location which minimizes pressure and heat losses through minimal bending and plumbing distance. Proper insulation will protect subsystems and operators from danger. Hydraulic power to the blower is provided by the central hydraulic system. Perhaps in the future, a drive train power take-off unit could be used to power other subsystems. The pyrometer is located just aft of the burner exhaust nozzle on the longitudinal sealant cart and between the sealant applicator and heater nozzle exit on the general process cart. Appendix E.2.1 contains the general specifications used in evaluating available commercial equipment and Appendix E.2.2 contains manufacturer's specifications for the major equipment purchased (exclusive of the flame safeguard unit and fuel train).

The Eclipse burner purchased, at maximum output, consumes approximately 28 LB of liquid propane (LP gas) per hour, meaning that for a normal eight hour work day, 224 LB of fuel could be consumed if run continuously. By outfitting the support vehicle with 2 additional vapor withdrawal 100 LB tanks, in addition to the 2 tanks already present for use with the melter, this consumption rate can be met.

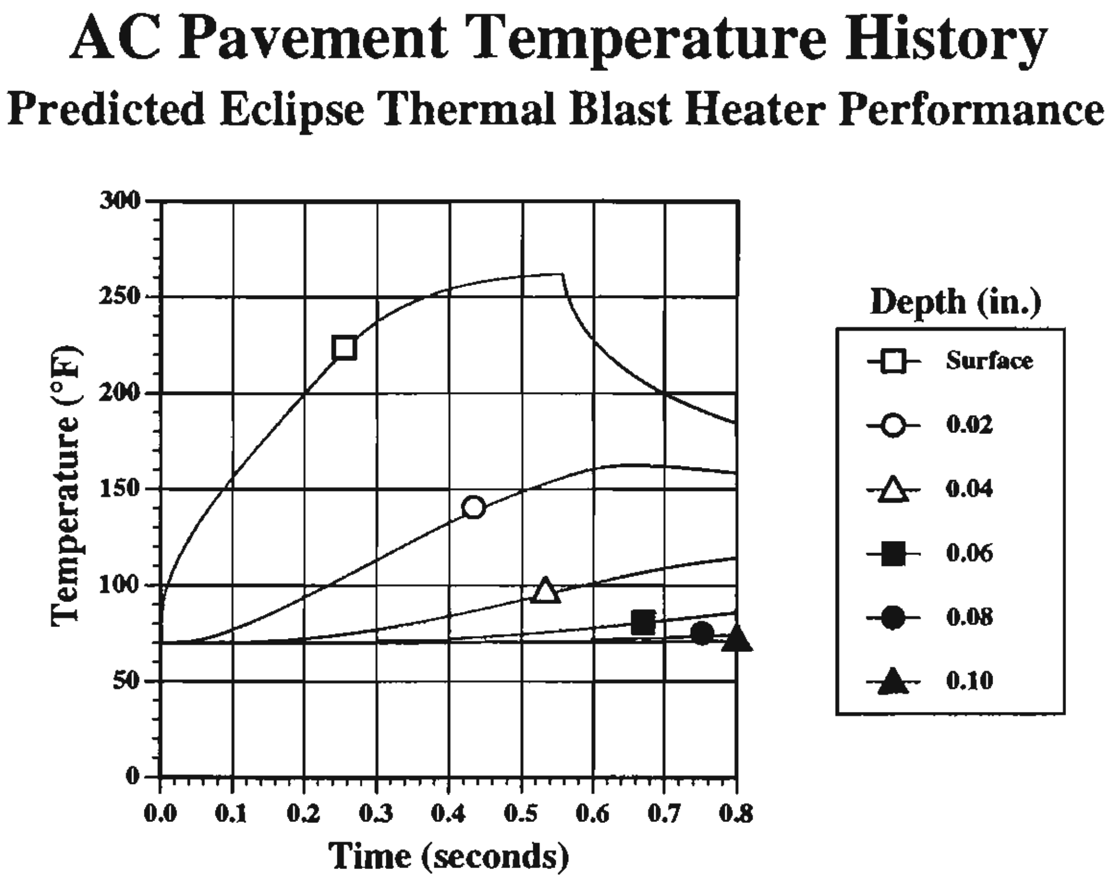

Figure 2.5.6 - Predicted Eclipse Thermal Blast Heater performance. Relative speed is 2 MPH, nozzle exit diameter is necked down to 2.5", and the exit gas temperature is set at 1500°F.

2.5.2.3 - Principles of Operation

Since both the debris removal and the surface heating portions of the HCD system require high volume / low pressure air, it is obvious that combining their required air flows into one centralized system, affords the possibility of utilizing a single blower. Vacuum air from the debris removal portion is therefore cleaned of debris in the separator unit, then exhausted to a burner, and blown onto the road surface to heat it to the proper temperature. This setup provides the best solution in terms of cost and efficiency. Figure 2.5.7 shows a conceptual sketch of this set-up deployed for longitudinal sealing.

The system is also designed such that it can operate in the CLEAN ONLY or HEAT AND CLEAN mode. In the CLEAN ONLY mode, the heater is not ignited and the blower is used by itself, with or without the debris removal attachment. This is a necessary feature since many DOTs do not heat

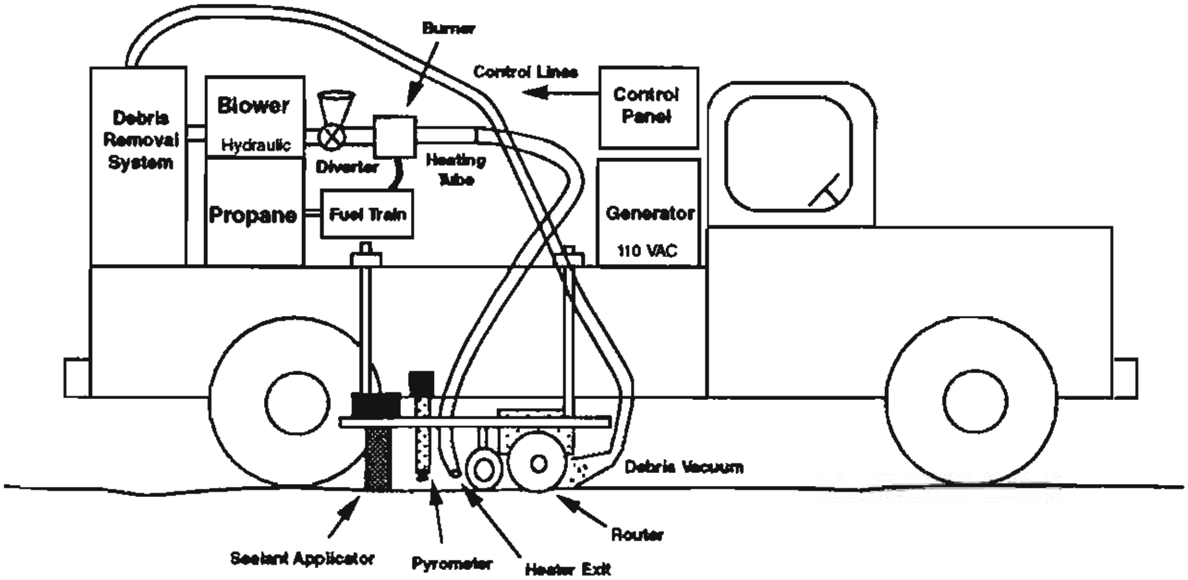

Figure 2.5.7 - Sketch of HCD system deployed for longitudinal sealing.

the roadway prior to sealing. The diverter valve is also necessary to adjust for the proper component pressure loads during system qualification. This will ensure maximum performance of the components while not causing damage to them.

Operation of the integrated unit takes place via a control panel to be mounted conveniently on the crack sealing vehicle. To begin operation, the unit is first configured for the type of sealing desired. (Some DOT's do not route or heat, others route and heat, while some may only route etc.) After configuration, the system is activated by first switching on the main subsystem power (assuming the ICU is in operation and power is present in the hydraulic system) then flipping solenoid switches that regulate hydraulic fluid flow to the blower. Normally the diverter should be set to divert flow from the pavement for safety reasons during start-up. After the blower reaches operating speed, the diverter valve can be released to deflect flow to the pavement enabling the burner to be ignited.

In general, the burner operates similar to most LP gas burner packages with a few exceptions. Ignition of the burner is automatically controlled by the flame safeguard system and takes place only after an air purge has been verified (1-5 seconds). Once ignited, the burner operates as a self contained unit as long as air flow is present. Should the air lines become clogged or the blower shut down, pressure switches sensing deviant air pressure would trip thereby shutting down the fuel flow. Fuel flow is normally maintained through a PID controller connected to the pyrometer -

as opposed to a manually or permanently set flow rate. Based on the surface temperature of the pavement, the pyrometer returns a signal, roughly between 12 and 16 mA (200°F and 300°F), back to the PID controller which in turn sends out a 4-20 mA signal, linear over the turn down range of the fuel control valve, either increasing or decreasing fuel flow in order to approach the desired surface pre-heat temperature. The burner output is therefore automatically proportionally adjusted for the set point programmed into the PID controller.

2.5.3 - Sealant Applicator

The sealant applicator unit constitutes a significant advancement in crack sealing technology. It was designed to deliver hot thermoplastic sealant at an increased velocity over current crack sealing techniques, as well as shape the material to produce a variety of sealant finish configurations. A significant advantage that this unit possesses over other sealing methods is that it uses a small amount of pressure to force sealant into the crack. The sealant flow rate is automatically adjusted according to the cross-sectional area of the crack as is described below.

During Phase II of this project, the design of the sealant applicator was finalized and a first generation prototype was built (see Figures 2.5.8 and 2.5.9). In Phase III the sealant applicator was successfully field tested (see Figures 2.5.10 and 2.5.11). In the following paragraphs, the principles of operation and a description of the various subassemblies is provided (see Figures 2.5.12 - 2.5.16).

2.5.3.1 - Subassembly A

Figure 2.5.12, Subassembly A shows the sealant supply tube. The hot-pour sealant is supplied to the tube through a Teflon hose from a melter unit mounted on the truck platform. During the time it takes for the sealant to flow from the melter to the pavement crack, the sealant must be kept at a high temperature in order to prevent the sealant from solidifying. To accomplish this, a continuous hot oil line is doubly wrapped around the Teflon hose. The line is broken when it reaches the sealant applicator and each end is mounted to the top of the subassembly (item 10). The entering oil sees a cavity in the shape of a half-circle (item 10, Section A-A), flowsthrough this cavity, then travels through an area between the sealant tube (item 1) and an outer wall (item 2). Two rods press-fitted between the sealant tube and the outer wall (item 32, Section B-B) force the oil to flow down the length of the sealant tube on one side and then back up on the other side where it exits.

Figure 2.5.8. The sealing dispensing unit mounted on the base plate for the longitudinal crack sealing machine.

Figure 2.5.9 - The sealant applicator at the end of the longitudinal machine.

Figure 2.5.10 - The sealing dispensing unit mounted on the longitudinal machine.

Figure 2.5.11- The sealant applicator sealing a crack.

Proper sealant application temperature is maintained by this design. High-temperature O-ring seals in the design insure that both sealant and oil do not leak outside the body or into each other.

At the base of the center tube (item 1) there is a cone-valve (item 7 mounted to item 9). The cone is spring-loaded, so when there is no sealant flowing, the sealant orifice is closed off. The force of the spring is just equal to the weight of a standing column of sealant. At the time when sealant is to be applied, pressure generated by the melter pump opens the cone-valve. When the applicator reaches the end of a crack, the sealant flow is stopped and the cone-valve closes, preventing extra sealant from flowing out of the tube.

2.5.3.2 - Subassembly B

During design it was necessary to address protection of temperature-sensitive parts of the applicator from the very high temperatures necessary to retain sealant fluidity. It is apparent that over a period of time, the entire Subassembly A will reach 350-400°F. This problem was solved in three ways: insulating material was used between Subassembly A and the rest of the applicator (Figure 2.5.13, items 4, 5 and 13), contact points were minimized (item 10), and heat fins were provided for maximum heat dissipation (item 6).

Another design issue concerned the manner in which the applicator would follow the contour of a road. All roads are not perfectly flat; i.e., surface irregularities are always present in pavement. The manner in which this problem is addressed is apparent by considering the drawing of Subassembly B. Three hardened Thompson shafts (item 3) are mounted between the upper and lower sections of the applicator (items 6 and 14). The shafts pass through three linear bearings captured in the frame. The result is that the entire sealant applicator assembly has the ability to move vertically over a range of 5.5" yet still be rigid in the horizontal plane. Overall, the modular design of the sealant applicator allows it to be mounted to the longitudinal machine, the general crack sealing machine, or any other compatible device.

The last design feature described using the Subassembly B drawing is the method by which the applicator controls the flow of sealant over a given crack. Consider the flow of sealant through the sealant tube (item 1). At the base of the tube, the sealant both fills up a crack and pushes a float (item 30) upwards (Circle A). The volume of sealant underneath the float is referred to as the reservoir. The float in turn extends three springs (between items 6 and 14) which are attached to a circular plate (item 35). A linear potentiometer, also attached to this plate, is part of a circuit where the output current represents the amount of sealant in the reservoir. The circuit controls a proportional valve which adjusts the rate of sealant flow.

As the applicator travels along a crack, a varying amount of sealant (dependent on crack width and depth) is pushed into the crack from the reservoir (Circle A). Note that the spring pushes against the float, forcing sealant into the crack. The internal sealant pressure in the reservoir is maintained between 2 and 8 PSI. As the float lowers due to sealant dispensing, the linear potentiometer circuit signals for an increase in sealant flow into the reservoir. Once the reservoir fills, the sealant flow is again decreased, etc. The closed-loop nature of the applicator provides continuous and complete filling of cracks independent of crack size and applicator surface speed.

2.5.3.3 - Subassembly C

As mentioned in the Phase I final report the sealant applicator is a combination sealant dispenser and shaper (squeegee). To provide for a wide variety of crack seal configurations, the rubber ring/squeegee at the base of the applicator was selected to have a 5" inside diameter (ID). During development and testing, a problem concerning the contact between the rubber ring and the ground was identified. The rubber ring could not flex on the road surface. As such, as is shown in Figure 2.5.15, Subassembly C, a steel cup brush (item 31) is used. This brush flexes on the road surface and provides for a flush sealant configuration over the crack. It is easily replaceable as it slips on and off an outer wall (item 17) and it is held in place by an adjustable clamp.

Proper operation of traditional squeegees requires a downward force of 10 - 20 LB. The weight of the sealant applicator is approximately 35 LB. Accordingly, this weight is counterbalanced by two compressed air cylinders (not shown) so as to provide proper down force.

Angular contact ball bearings permit the rotation of the tubing ring providing for other sealant configurations (e.g., overband) as mentioned in the Phase I final report. This rotation additionally provides for more uniform wear of the tubing ring and reduces the possibility of sealant buildup on the ring (item 31). The bearings are mounted within the applicator body, away from the base to protect them from the environment (items 15, 18, 19 and 27). A V-belt drives all the various rotating components through a pulley (item 11) mounted to the outer wall (item 17).

2.5.3.4 - Subassembly D

Figure 2.5.16, Subassembly D shows a half-view of the entire sealant applicator assembly. On the left, a flexible link connects a variable speed DC motor on the truck drives a shaft (item 34). The shaft has a raceway for a ball bearing which is mounted to a smaller pulley (item 28). The bearing acts in two ways: 1) it allows the pulley to move up and down with the main body of the applicator as it travels down the road and, 2) it allows the pulley to spin due to the rotation of the shaft. The shaft assembly can also be moved back and forth in guiding groves (items 25 and 26) in order to adjust tension and change the belt that rotates the tube assembly. As noted above, this rotation provides for more uniform tubing ring wear and less sealant build-up. It was also determined during testing that a pulse rotation for squeegee wear produced a better seal than continuous rotation.

2.6 - Vehicle Orientation And Control System (VOC)

2.6.1 - System Description

The Vehicle Orientation and Control (VOC) system tracks the position of cracks on the road surface with respect to a fixed point (e.g. the robot base) located on the truck. This system is required so that the position of road cracks identified by the Vision Sensing System (VSS) at the front of the crack sealing truck can be tracked continuously as the truck moves forward, until the cracks enter ithe work space of the robot arm at the rear of the truck. At that point, the crack position data will be sent to the controller on the robot arm (RPS) via the ICU. The robot controller will then send signals to position the end effector of the robot arm over the cracks. Once positioned, the end effector will rout, clean, heat, and finally seal the cracks. It is our intent that ultimately the entire process of identifying the cracks, tracking their positions, positioning the robot end effector, and performing the crack repair operation will be done in a continuous fashion with the truck moving ahead at a slow forward speed. A schematic illustration of the crack sealing truck and the integrated VOC, VSS, RPS, and ICU is given in Figure 2.6.1.

The task of tracking points on a crack would be simple if the truck were moving straight ahead or if it were turning a corner of constant radius. However, this is usually not the case. To illustrate this point, it is noted here that after a particular point on a crack is identified by the VSS, the truck must move ahead approximately 35 feet before that same point on the crack moves into the work space of a robot arm. Throughout this distance it is unlikely that the truck will maintain a straight heading or even a turn of constant radius. Instead it is very likely that the truck will be moving with many combinations of left and right turns (of various radii) and straight ahead motion. The heading variations may be small but they will be significant enough to have a large impact on the accurate positioning of the robot end effector.

2.6.2 - Principles of Operation

The entire VOC system will use digital communication. Two (2) optical, rotary, incremental encoders will each be mounted on separate "fifth wheel" assemblies. The fifth wheel assemblies

Figure 2.6.1 - Crack sealing truck showing integrated VOC, VSS, RPS, and ICU (conceptual illustration only).

will be mounted on either side of the truck outside of the rear wheels and midway between the two rear axles of the truck so that the center line of the encoders passes through the center of rotation of the truck (see Figure 2.6.2). The fifth wheel assemblies will be located approximately 10 feet apart. The fifth wheel assemblies will continuously monitor the change in position of each side of the truck. From position data obtained from the encoders, the translation of the truck (laterally

Figure 2.6.2 - Placement of encoders on crack sealing truck.

with respect to the road surface) and rotation of the truck (yaw - about a vertical axis with respect to the road surface) can be continuously calculated.

An on-board computer will also be a part of the VOC. This computer will serve several functions. In general, crack position data will be sent to the VOC computer from the VSS and truck position data will be gathered from the encoders on the fifth wheels. Calculations of truck position and orientation and crack position (with respect to the truck) will be performed by the VOC computer. This information will be shared with the ICU. The VOC computer will also update the path planning module in the ICU. Finally, the VOC computer will send current crack position data to the RPS for immediate crack sealing.

More specifically, the VOC computer will perform as follows. The Cartesian reference frame used by the computer program will be fixed on the truck near the center of the rear bumper. This reference frame will move (in position and orientation with respect to the road surface) as the truck moves. The VOC computer will receive (from the VSS) the position, perpendicular to the direction of travel of the truck (with respect to the truck), of points on cracks as they are identified by the VSS camera at the front of the truck. The VOC computer will note the time instant when this data was received. Then the VOC will begin tracking the change in position and orientation of the truck with respect to the time instant when the data was received from the VSS by sampling data (at a set time frequency) from the right and left encoders. When the crack moves into the work space of the RPS and is immediately ready to be sealed, the VSS will perform a final calculation of points on the crack with respect to the truck, and transform the coordinates into the RPS frame of reference. This information will be sent immediately to the RPS so that the RPS end effector can clean, heat, and seal the crack. Once the crack repair operation is completed on that particular portion of crack, that crack segment will no longer be tracked by the VOC computer. Refer to Figure 2.6.8 for a flow chart of the integration of the VOC with the VSS, RPS, and ICU.

2.6.3 - The Use of Fifth Wheels

One design consideration that merits some discussion is the decision to mount the position encoders on fifth wheels rather than attaching them directly to the tires of the crack sealing truck. There are several advantages to the fifth wheel design. These advantages follow.

- All drive train noise that is transmitted through the truck wheels is not transmitted to the encoders.

- The wheel base distance can be increased if necessary to allow greater accuracy in computing the vehicle position and orientation.

- Noise coming from the truck and various systems can be dampened through the fifth wheel connection (to the truck) so that the noise is minimized by the time it reaches the encoders.

- The truck tires are subject to fluctuations in radius caused by tires of low stiffness and changes in tire pressure, vehicle weight, consumable materials fluctuations, number and weights of persons riding the truck, vibrations, etc. Nearly all problems caused by changes in tire diameter can be eliminated through the use of a relatively high stiffness wheel attached to a fifth wheel assembly. This would allow for greater accuracy in the encoder data since fluctuations in wheel radius will be minimized.

- For a tandem axle truck that is turning any sort of corner, the tires of one of the rear axles must always "scrub" sideways slightly. If more of the vehicle weight is resting on the front rear axle, the back rear axle tires will do the majority of scrubbing. Conversely, if more of the vehicle weight is resting on the back rear axle, the front rear axle tires will do the majority of scrubbing. This phenomenon effectively changes the distance between the front of the truck (where the VSS cameras are located) and the rear axle that is in contact with the road surface. This change causes a slight error in the results of the kinematics equations used for the VOC system. This error can be minimized by centering the encoders midway between the rear axles of the truck. As an added benefit, the scrub on the encoder wheels is minimized. The fifth wheel is an effective design feature for mounting the encoders midway between the rear axles of the truck.

- The fifth wheels can be designed to be more sensitive to the road surface than truck tires by optimizing design characteristics such as damping, wheel stiffness, road/wheel contact force, natural frequencies of fifth wheel components, etc.

2.6.4 - Position and Orientation Kinematics

2.6.4.1 - Introduction

The task of tracking points on a crack would be simple if the truck were moving straight ahead or if it were turning a corner of constant radius. However, this will probably not be the case. To illustrate this point, it is noted here that after a particular point on a crack is identified by the VSS, the truck must move ahead approximately 35 feet before that same point on the crack moves into the work space of the robot arm. Throughout this distance it is unlikely that the truck will maintain a straight heading or even a turn of constant radius. Instead it is very likely that the truck will be moving with many combinations of left and right turns (of various radii) and straight ahead motion. The heading variations may be small, but they will be significant enough to have a large impact on the accurate positioning of the robot end effector.

To accomplish the complicated task of tracking road cracks with respect to the crack sealing truck, it is necessary to develop the proper kinematics of the problem and incorporate them into the VOC computer program. The kinematics of the crack tracking problem are developed in the sections that follow. It is noted here that since the maximum speed of the truck during the crack sealing operation likely to be not more that 2 MPH, dynamic effects of the truck and the various ACSM subsystems have a negligible effect on the crack tracking problem. Therefore, it is possible to get a very accurate solution to this problem by including only the kinematic equations of the systems involved.

2.6.4.2 - Definitions

Subscripts

$_{[\#/\#]}$ - Any subscript of the form [#/#] identifies the variable to which it is attached as having its particular value between step "[#/" and step "/#]" of the truck. An example is [4,5]. The variable to which this subscript is attached has its particular value between step 4 and step 5 of the truck. A general example is "[n-1/n]". The variable to which this subscript is attached has its particular value between step "n-1" and step "n" of the truck.

$_{\#}$ - Any subscript not contained within "[ ]" identifies the coordinate frame from which the value of the variable to which the subscript is attached is measured with respect to. For the example of "4" the variable to which this subscript is attached is measured with respect to the 4th moving coordinate frame (4th step of the truck). For the example of "n-1", the variable to which this subscript is attached is measured with respect to the "n-1" moving coordinate frame. For the example of "0", the variable to which this subscript is attached is measured with respect to the "0" or fixed coordinate frame.

$_{[\#]}$ - Any subscript of the form [#] identifies the variable to which the subscript is attached as having the particular value for step "#" of the truck. An example is "[3]". The variable to which this subscript is attached has the particular value for step "3" of the truck. A general example is "[n]". The variable to which this subscript is attached has its particular value for step "n" of the truck.

Constants

D - The lateral distance (in the "y" direction) between the left encoder wheel and the right encoder wheel. Refer to Figure 2.6.3.

Ne - The total number of encoder pulses per revolution of the encoder wheel (fifth wheel). Refer to Figure 2.6.10.

Re - The radius of the encoder wheel. Refer to Figure 2.6.10.

W - The lateral distance (in the "y" direction) between the right encoder wheel and the point "B" located on the truck. Refer to Figure 2.6.3.

Variables

Angles

$\beta_{[\#]0}$ - The angle, about a vertical axis, from a line drawn through point "$B_{[0]}$" and parallel to the x-axis of the "0" (fixed) reference frame to a line drawn through point "$B_{[0]}$" and point "A". The subscript "[#]" denotes the step of the truck motion to which this value belongs. Refer to Section 2.6.4.2.1 and Figure 2.6.4. This angle is defined and used only for intermediate manipulation of the kinematics formulas. In the final equations it is eliminated through reverse substitution. This variable makes sense only when referring to the "$_0$" reference frame.

$\phi_{[\#]}$ - The angle, about a vertical axis, from a line drawn through point "$B_{[0]}$" and parallel to the x-axis of the "#-1" reference frame to a line drawn through point "$B_{[0]}$" and point "A". The subscript "[#]" denotes the step of the truck motion to which this value belongs. Refer to Section 2.6.4.2.1 and Figure 2.6.4. This angle is defined and used only for intermediate manipulation of the kinematics formulas. In the final equations it is eliminated through reverse substitution.

$\psi_{[\#-1/\#]}$ - The angle, about a vertical axis, from a line drawn through point "$B_{[\#-1]}$" and point "$B_{[\#]}$" to the x-axis of the "#-1" reference frame. The subscript "[#-1/" refers to point "$B_{[\#-1]}$". The subscript "/#]" refers to point "$B_{[\#]}$". Refer to Section 2.6.4.2.1 and Figure 2.6.4. The value of this angle is independent of the reference frame with respect to which it is measured. This angle is defined and used only for intermediate manipulation of the kinematics formulas. In the final equations it is eliminated through reverse substitution.

$\theta_{[\#]}$ - The angle, about a vertical axis, through which the truck rotates. The subscript "[#]" denotes the step of the truck motion at which this rotation occurred. This angle is commonly referred to as the "yaw angle". The value of this angle is independent of the reference frame with respect to which it is measured. Refer to Section 2.6.4.2.1 and Figure 2.6.4.

θTotal - The sum of all "$\theta_{[\#]}$" values up to and including the present step of truck motion.

1

Introduction

1.1 - Study Objectives

Worldwide, a tremendous amount of resources are expended annually maintaining highway pavement. In California alone, the state Department of Transportation (Caltrans) spends about $100 million per year maintaining approximately 33,000 lane-miles of flexible pavement (Asphalt Concrete - AC) and 13,000 lane-miles of rigid pavement (Portland Cement Concrete - PCC). A portion of these maintenance activities involves the sealing and filling of cracks (approximately $10 million per year) which, when properly performed, can help retain the structural integrity of the roadway and considerably extend the mean time between major rehabilitation.

The sealing and filling of cracks are tedious, labor-intensive operations. A typical operation to seal transverse cracks in AC pavement involves a crew of eight individuals which can seal between one and two lane miles per day. The associated costs are approximately $1800 per mile with 66% attributed to labor, 22% to equipment and 12% to materials. Furthermore, the procedure is not standardized and there is a large distribution in the quality of the resultant seal. In addition, the crack sealing work team is exposed to a great deal of danger from moving traffic in adjacent lanes.

The ultimate goal of the SHRP H-107A project is to develop prototype automated machinery that will sense, prepare, and seal (or fill) cracks and joints on pavement. As such, the primary objectives of this project are to design machinery for the sealing and filling of joints and cracks in pavement in order to:

- Increase the cost-effectiveness of these operations,

- Increase the quality, consistency, and life of the resultant seals and fills,
- Increase the safety of workers and highway users, and
- Increase the use of remote operation and control of equipment to attain the above.

Machinery that satisfies these objectives will additionally reduce lane and highway closures and thus, will play a significant role in reducing traffic congestion, an area of considerable concern in the major urban regions around the world. The cost effectiveness of such machinery comes from a combination of the increased speed and reduced manpower needs, in addition to the higher quality seal which will reduce the frequency of major highway rehabilitations.

In order to have the greatest impact, such machinery should satisfactorily perform the following functions automatically:

- Sense the occurrence and location of cracks in pavement.
- Adequately prepare the pavement surface for sealing/filling with the appropriate methods; for example, any operation that is deemed necessary such as removing entrapped moisture and debris, preheating the road to ensure maximum sealant adhesion, refacing of reservoirs, etc.
- Prepare the sealant/filler for application; i.e., heat and mix the material, etc.
- Dispense the sealant/filler.
- Form the sealer/filler into the desired configuration.
- Finish the sealer/filler.

Additionally, as overall functional specifications, this machinery should be:

- Reasonable in cost,
- Easy to use,
- Reliable and fast,
- Rugged,
- Safe,

- Capable of being driven on the highway under its own power,
- Self-contained (contain all of the components necessary to perform task),
- Primarily powered by an internal combustion engine,
- Carry sufficient fuel supply for a normal day's operation,
- Provided with a heavy duty electrical system with sufficient capacity for safe operation of all components,
- Compatible with repair materials to be identified under SHRP H-106,
- Fabricated in such a manner that the eventual addition of safety lighting & appurtenances (arrow boards, etc.) is possible, and
- Compliant with any applicable OSHA standards.

Furthermore, the equipment prototypes may be derived from modifying existing equipment or from the development of new equipment, and each equipment design may include one or more pieces of equipment.

In this section of this report, we will present our approach to the development of the machinery. We will first establish the intended functions of the machine in terms of the various sealing and filling operations that the machinery is expected to perform. The initial functional requirements, which drove the machine and component concepts, will be presented. We will then present the machine system architecture, followed by description of the integrated machine concept.

1.2 - Development Plan

The objective of this project has been to develop, fabricate, test and demonstrate prototype equipment that will perform joint and crack sealing/filling in concrete and asphalt pavements. Desirable improvements would be in the direction of enhanced speed, efficiency, quality, and safety. It is believed that the development of an automated crack/joint sealer with the above-noted improvements is feasible. Such a machine would operate at least at the speed for currently available more labor-intensive methods, and would perform to the quality level widely obtainable by such methods. Because the equipment would be self-contained and automated, it would reduce the exposure of maintenance crews to traffic, thereby also resulting in enhanced safety.

As part of the H-107A project, a detailed feasibility study was presented as part of the Phase I Report. While this study examined many of the current practices, it was not an objective of SHRP H-107A to identify whether sealing cracks or joints makes sense, nor what the best method is of performing these maintenance operations. These issues have been addressed in the past, and two other SHRP projects are also addressing these issues. In SHRP H-101, the *effectiveness* of crack sealing in asphalt concrete (AC) pavements is being studied to see if sealing cracks improves the performance of the pavement in comparison to similar pavements without sealed cracks. SHRP H-101 is using more or less standard materials and procedures to seal these cracks. SHRP H-106 does not address effectiveness of crack sealing at all, but looks at the *performance* of various materials and procedures used for crack sealing in AC pavements and joint resealing in PCC pavements.

Therefore, between H-101 and H-106, it may be determined whether or not crack sealing is an effective maintenance technique and what materials and procedures work best in sealing a pavement. These two projects are field experiments, however, whose results may not fully be known or analyzed in the next 3 years. This is long after H-107A will be completed. A major issue was how the H-107A should proceed to ensure that it speaks to the issues of the RFP while avoiding built-in obsolescence should the results from the other SHRP research efforts point in a different direction? This portion of this report presents the development plan, approved early in the project, that simultaneously addresses the objectives of this project and avoids obsolescence of the resulting product. This part of the report also summarizes the findings of the earlier feasibility study. While H-107A is not directly evaluating the crack sealing operation, we have elected to examine the currently used machinery and techniques, which are inherently linked, in order to develop the best, and most versatile, machine. As such, in the feasibility study, we have recommended existing devices that we feel are suitable for an automated machine, and additionally, we have discussed specific developments that would enhance performance.

1.2.1 - Assumptions

The developments in H-107A are based upon several key assumptions that bear discussion. Because of the state of flux of pavement sealing technology, it was assumed that it would be inappropriate to try to develop from the start a piece of equipment that is able to use the most innovative materials and procedures to seal cracks and joints. Instead, a modular approach has been taken to the development of the equipment that will allow, without excessive cost or rebuilding, the addition or substitution of different elements of the equipment, each of which represent different activities in the sealing process. The modular approach has been central to the success of the project. It removed the emphasis from guessing what the most successful materials and procedures will be and allowed the focus of this project to shift toward the general operations, the automated sensing of cracks, and the mechanical operations.

In discussions with SHRP staff, it was confirmed that the crack sealing vision system need not be able to identify when to seal cracks. This type of information would likely come from an automated distress survey, and it might be in the form of "crack sealing needed between MP xx.x and xxx.x." Thus, it is likely that a decision would already be made based on the existence of the right type of cracks, and the machine itself would not have to differentiate between alligator cracking, fine transverse cracking, and/or other conditions that might not be appropriate. What remained to be determined then, is the type of decision system that would be used to identify the suitability of a section of pavement for this type of equipment. Another important feature was the determination as to whether the vision system would need to identify localized areas that should not be sealed in a general section that is being sealed.

There are perhaps five types of pavement sealing that must be addressed by the prototype equipment developed in this project. These are:

- AC/PCC longitudinal crack sealing.
- PCC longitudinal joint sealing.
- PCC transverse joint sealing.
- AC transverse crack sealing.
- PCC transverse crack sealing.

The longitudinal sealing operation is perhaps the easiest and fastest to perform. Longitudinal cracks and joints tend to be uniform, occurring as reflective cracks above longitudinal joints in PCC pavements, as cold joints between separate passes of an AC paver, as a longitudinal joint itself in a PCC pavement, or as the longitudinal joint between a mainline PCC pavement and the adjacent shoulder. The area to be sealed in these cases is very straight over a comparatively long distance, and locating and sealing the joint/crack are simple activities. Preparation consists of either sawing or routing to form a reservoir and cleaning out the reservoir prior to application of the sealant. With only a few exceptions, very little movement is expected at these joints, which makes sealing them well an easier task than other sealing activities. The longitudinal sealing operations, when performed using current practices, is the fastest of the five.

PCC transverse joint resealing is only slightly more difficult. In PCC joint resealing, a straight reservoir is located at regular intervals or in a regular, repeated pattern. These are easily identified, are found in known locations, and are expected to be straight. Preparation prior to resealing can include routing, sawing, and plowing to remove debris and old sealant, and water blasting, sand blasting, or air blasting to prepare the joint for new sealant. Prior to placement of the sealant, the placement of a backer rod may be specified in order to achieve a desired shape factor. The sealant, when placed, may require tooling at the surface or the material can be self-leveling.

Because joints are built into the pavement and are not a defect, expectations for sealant performance are greater here than in other applications. Typically, these will be more highly engineered and thus more care is taken in the design, selection of materials, and construction of resealed PCC joints. It is assumed that a project would be identified as a suitable candidate for joint resealing by some other means.

AC crack sealing is the most complex operation of the five to be addressed in this project. PCC crack sealing is similar, but it is performed much less frequently. There are many different types of cracks that are present on a pavement surface. They are rarely uniform in width or spacing, follow random patterns, and can change in nature (e.g. from tight to wide or from clean to spalled) from one location to the next. Because of the many variables associated with AC crack sealing, we will devote a significant part of our initial research efforts of towards this method. Additionally, since longitudinal operations are the fastest and simplest, we will concurrently address this operation. By employing many of the same components for these two operations, we will clearly show the modularity of our machine, and the potential to address all other types of sealing which fall in between in terms of difficulty. It is believed that adaptation of automated crack sealing equipment to the other operations is a trivial event in comparison to the challenge associated with the automated sealing of cracks in AC pavements. The rest of this document more narrowly defines characteristics of the AC crack sealing operation that are believed to be important in defining the abilities of the prototype equipment.

1.2.2 - Crack Sealing Approach

There has been a significant amount of research time and effort spent on identifying the appropriate means of sealing cracks; e.g., Blais, 1984; Belangie & Anderson, 1985; Chehovits & Manning, 1984; Chong & Phong, 1984, 1987; Turgeon, 1989; Smith, et al. 1991; Wolters, 1973. The following discussion applies some of the findings of the above-referenced research studies, concentrating on those portions that apply to the sealing of cracks in bituminous pavements. It should be noted that the greatest body of research on this topic has been conducted, with a few exceptions, in regions subjected to fairly harsh winters (Utah, Minnesota, Ontario, Delaware, Georgia, Montana, and Tennessee) and, in most cases, excessive moisture. Their findings must be considered as representative of conditions in which the environment has the most severe effect on pavement performance.

Causes and Development of Cracks

Cracks in AC pavements are caused by many different factors. In general, causes can be divided into load-related cracks, environment-related cracks (temperature, moisture), pavement materials problems, and cracks caused by failures associated with the existing subgrade. While the causes are certainly of interest, the types of cracks that should not be sealed are adequately identified through the specification of other criteria, such as crack width, orientation, volume, and density.

If there are too many cracks, it is both uneconomical to seal them, and unsound from an engineering standpoint. Generally speaking, too many cracks are indicative of a pavement in an advanced state of deterioration. At that point, the pavement is more likely a candidate for major rehabilitation or reconstruction. This approach eliminates from consideration a pavement with fatigue or alligator cracking, or one with serious block cracking. Even a pavement that exhibits primarily transverse cracking may be ruled out as a candidate for sealing if the cracks are too closely spaced or excessively wide. One study recommended that pavements with cracks closer than 25 ft should not be considered for crack routing and sealing because that would indicate a later stage of deterioration in which crack sealing would not be effective in prolonging pavement life (Chong and Phang, 1984).

Crack width

It is generally recognized that there is a range of crack widths within which crack sealing is practical. Extremely narrow cracks are not considered suitable candidates for several reasons. Generally, they are not a major source of moisture infiltration for a pavement. Also, substantial routing or sawing would be required in order to make narrow cracks wide enough to place sealant material within the crack. Such routing would unduly damage the pavement when the cracks are so narrow. Very narrow cracks are also difficult to track on a pavement surface, further supporting the contention that they are not yet candidates for sealing.

On the other hand, cracks that are too wide tend to be indicative of more serious problems. They most likely extend through to the bottom of the pavement and will have significant movement associated with them. With such movement, most available sealants will not last very long. Furthermore, by the time such a crack is found, distresses associated with the presence of excess moisture may have started to develop.

Studies which specifically addressed crack width as a sealing criterion were fairly consistent in their recommendations. Chong and Phang recommended that cracks between 6 and 12 mm (approximately 0.25 to 0.5 in) were candidates for routing and sealing; narrower cracks were to be left alone and wider cracks were simply to be cleaned and sealed (Chong and Phang, 1984). The Value Engineering study of crack sealing recommended that cracks wider than 0.19 to 0.25 in were to be sealed, although no upper limit was recommended (Belangie and Anderson, 1985). Utah recommended that cracks between 0.19 and 1.0 in wide were candidates for crack sealing (Blais, 1984). A review of the available literature on the topic suggested that cracks between 0.20 and 0.60 in wide be considered as suitable for sealing by the automated sealant equipment.

Crack Length

Cracks should be of sufficient length to justify sealing. For transverse cracks, this means that they will run most of the width of the pavement. Interconnecting cracks, such as primarily longitudinal-diagonal or longitudinal cracks, will also be sealed if sufficiently long. In combination with the crack width criteria, it is believed that a minimum length of 3 to 6 ft is appropriate. Shorter cracks should be avoided because they are either in the process of becoming longer cracks or because they will most likely be narrower and have associated with them less movement. Sealing will not stop the further development of a crack that is not fully formed. The crack will continue to develop and the sealing effort will have been wasted, as a crack that is only partially sealed will not keep moisture out of a pavement.

Random Crack Orientation

It is believed that most of the cracks for which automated crack sealing is a viable alternative will run primarily transverse to the direction of travel. There may be some diagonal cracking or longitudinal cracking (other than those located at seams and joints), but generally transverse cracks occur several years sooner than other cracks and would therefore need to be sealed sooner.

Thermal cracks, with which are associated the greatest amount of movement, also generally run in a transverse direction.

Reservoir Dimensions

The shape of the reservoir has a large effect on sealant performance. The shape is characterized through the ratio of the sealant depth to reservoir width, also known as the shape factor. The desired shape factor is a function of the type of sealant selected and the expected movement at the crack. A variety of approaches are used for both rubberized asphalt sealants as well as for silicone sealants. Low profile channels have received increased attention with popular dimensions being 10 mm deep by 40 mm wide and 0.2" deep by 1.5" wide.

Crack Preparation

Most studies have recognized and emphasized the importance of the proper preparation of the crack. The first step in the preparation of the crack calls for the removal of loose materials from the crack and the creation of the properly-dimensioned reservoir to accept the sealant. Routers are probably the most commonly used equipment to perform this function for cracks in AC pavements.

Routers are relatively quick and very maneuverable, which allows them to be able to closely follow a meandering crack. Routers will produce some spalling along the edges of the crack, but generally not enough to create any problems for the application of the sealant. While saws provide a more uniform and perpendicular cut, routers are generally preferred for cracks because of their maneuverability. Vertical spindle routers cause less spalling than rotary impact routers, but are much slower than the rotary routers. The use of carbide-tipped bits on the rotary impact router helps to mitigate the spalling.

We should note that some controversy exists relative to the use of routers for reservoir creation. While we do not expect to resolve this issue, the modularity of our machine will allow operations with or without the use of routing. Additionally, the automation of the operation may have a significantly positive effect on the cost-effectiveness of routing.

Reservoir Cleaning

The crack reservoir must be clean and dry prior to placement of the sealant. A number of methods have been used to clean cracks in a sealing operation. Air blasting can be used to clean the reservoir faces, but is not successful in removing any laitance or material bonded to the reservoir face. A hot compressed air (HCA) lance, or heat lance, not only delivers air under pressure, the air is also hot enough to dry out moisture in the crack and the adjacent pavement.

There are several other methods that are available for crack preparation. Sand blasting and shot blasting have the advantage of being abrasive enough to remove laitance on the reservoir face. Compressed air blasting is still required after their use, however, to remove the dirt and material left by those cleaning methods. In the use of sand or shot blasting, there are additional safety precautions that must be followed.

Water blasting has seen some use, but is not really appropriate for AC pavements. While it may be useful to prepare concrete pavements, it also leaves the pavement wet, and most sealants cannot be applied until the pavement is dry. Safety is also a major concern when using water blasting. Crack saws have seen increasing use for reservoir preparation. The technology has not been totally successfully applied to cracks because of the difficulty in following their meandering path.

The HCA lance is probably the best compromise of existing devices for cleaning out the material from the crack since it also serves the dual purpose of drying out the crack and adjacent pavement. To automate the use of existing hot-air lances would require extensive modifications, and thus, a new form of heat lance was proposed as part of this project. With the use of a heat lance, it is essential that the pavement not be overheated, and care should be taken not to burn the pavement, nor to drive off too much of the light fractions of the asphalt.

Material Type

There are two broad types of sealant materials that are commonly used for crack sealing. These are thermoplastic materials that can be applied either hot or cold, and thermosetting materials, that are applied cold. The most commonly applied materials are hot-applied thermoplastics. Materials in this category are representative of those that have average or above performance and can be expected to provide 3 to 5 years of sealing if properly applied.

Sealing Configuration

A major issue in crack sealing for asphalt pavements is the surface configuration of the sealant. The choices are a recessed sealant, a flush sealant, and an overbanded sealant. Each approach has its advantages and disadvantages and these have been discussed in detail in the literature.

1.2.3 - Summary and Plan

The sealing of cracks and joints in both AC and PCC pavements has been extensively researched in the past, and it was not within the scope of H-107A to try to ascertain the best method to seal pavements. For the purposes of this project, the automated equipment should incorporate sealing methods and materials that are in widespread use and have been shown to be effective. The developed equipment should enable the prototype to be fairly adaptable, so that findings from H-106 and perhaps other research can be used to modify the equipment should that be deemed necessary.

As such, we have developed a hierarchy of crack sealing operations in terms of difficulty in order to limit the functional requirements of the prototype machinery. The easiest and most difficult operations are longitudinal AC/PCC sealing and transverse crack sealing, respectively. These two operations have been chosen as those that the prototype machinery should address. Furthermore, due to their many unique features and the fact that they are sealed much more frequently, we have elected to address AC transverse crack sealing initially. By developing machinery to address the "upper" and "lower" bounds in terms of difficulty, we feel that the modifications necessary to address other types of crack repair will be relatively minor involving such things as providing different types of end-effectors. By developing machinery to address the "easiest" and "most difficult" operations, the feasibility of the machinery to address any other operations should be clearly established. Finally, the two operations noted are quite common and thus, such machinery has the potential to find widespread application.

Along these lines, the following list summarizes the initial functional requirements of the prototype machinery developed under SHRP H-107A:

- The machine shall operate on cracks that are between 0.2 and 0.6 inches wide.
- The machine shall operate on cracks that are at least 3 feet long.
- The machine shall have the ability to prepare a crack reservoir with a router.

- The machine shall clean and heat the reservoir with some form of a hot air lance.
- The sealant material will be a hot-applied thermoplastic.
- The sealant should be placed approximately flush with the surface of the pavement.

Later in this document, we will discuss the recommended component modifications to allow all types of crack sealing and filling operations to be performed.

1.3 - Machine System Architecture

With consideration of the range of activities required of an automated crack sealing machine, a general machine system architecture was devised. In addition to the support vehicle itself, the total machine includes seven subsystems. A block diagram of the total machine architecture including block diagrams of the individual subsystems is included in Figs. 1.1-1.8. To follow is a short description of each system.

Integration and Control Unit (ICU): The ICU acts as a clearing house for all information flow. Many of its functions are listed in the block diagram. Fundamentally, this unit includes the ability to communicate with all the systems and the ability to process the information. The ICU oversees the entire operation and coordinates the activities of the other subsystems. The information forwarded from the Vision Sensing System (VSS) will be translated into a planned path for the Applicator and Peripherals System (APS) components (crack/joint preparation equipment, etc.). Thus, the ICU will include the necessary algorithms to plan a crack/joint sealing path.[1] If multiple end-effectors are employed, the ICU will need to first allocate cracks to the individual applicators and will do so in a manner to maximize speed and avoid interference. This system keeps account of the actual position of the total machine and its components by interacting with sensors on the Robot Positioning System (RPS). It additionally monitors the APS to ensure adequate volume and temperature of sealant/filler, air, etc. Following the planning of the appropriate path(s), the ICU controls the motion of the applicator(s) with the interaction of the Local Sensing System (LSS) and it additionally controls the individual applicator functions.

System Display Unit (SDU): The SDU provides for any interactions with the machinery operator. It provides information on the machinery status, and it allows for the operator's inputs to the ICU.

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[1] The path planning function is actually performed by the Path Planning Module. Since this module is housed within the ICU, we do not distinguish it as a separate system for machine architecture purposes. Later in this document, however, it will be discussed independently of the ICU.

It is unrealistic to expect that an integrated machine of this type will work with no operator involvement; i.e., it is not an autonomous machine. As such, this system offers the operator a convenient means for interacting with the machine.

Vision Sensing System (VSS): This machine vision based sensing system is capable of viewing the entire width of the roadway and providing crack information (location and orientation) to the ICU in sufficient detail so that crack preparation, sealant/filler application, and shaping can be performed automatically. This system includes camera, image processing equipment, and necessary supplemental lighting. The VSS is provided vehicle position and speed information from the Vehicle Orientation and Control System (VOC). This is necessary in order to accurately determine relative crack positions. Information from this system is used to plan the path of the APS's end-effectors in the ICU.

Robot Positioning System (RPS): The RPS positions the APS end-effectors according to the path planning information provided by the ICU. The path dictated by the ICU includes both positional and speed information. The RPS has sensors that feed back actual speed and position information based on joint coordinates and velocities in order to modify trajectories in the ICU according to additional information including vehicle speed, etc. The RPS also positions the Local Sensing System.

Local Sensing System (LSS): The LSS is a laser range finder based system, and it is used to both verify the presence of cracks identified by the VSS and to participate in the APS path. The LSS includes both the actual sensor and the support processor. The LSS has the potential to provide information on crack depth and width in addition to extremely accurate positional information.

Applicator and Peripherals System (APS): The APS includes all the components that actually operate on the roadway and all the peripheral hardware such as air compressors, melter, propane tanks, etc. The APS end-effector components are positioned by the RPS and all components are provided instructions from the ICU. The APS includes a wide assortment of sensors that provide information on each of its components to the ICU for instructions. The ICU in turn provides APS status information to the operator through the SDU for his information and possible attention; i.e., notification of empty sealant tank, etc.

Vehicle Orientation and Control (VOC): The VOC provides vehicle motion measurements to the ICU and VSS. The VOC includes all necessary hardware to measure vehicle speed and orientation. In future commercial machinery, we anticipate that the VOC will additionally be required to control motion of the support vehicle, and as such, the VOC will have the necessary sensors and actuators to perform this task.

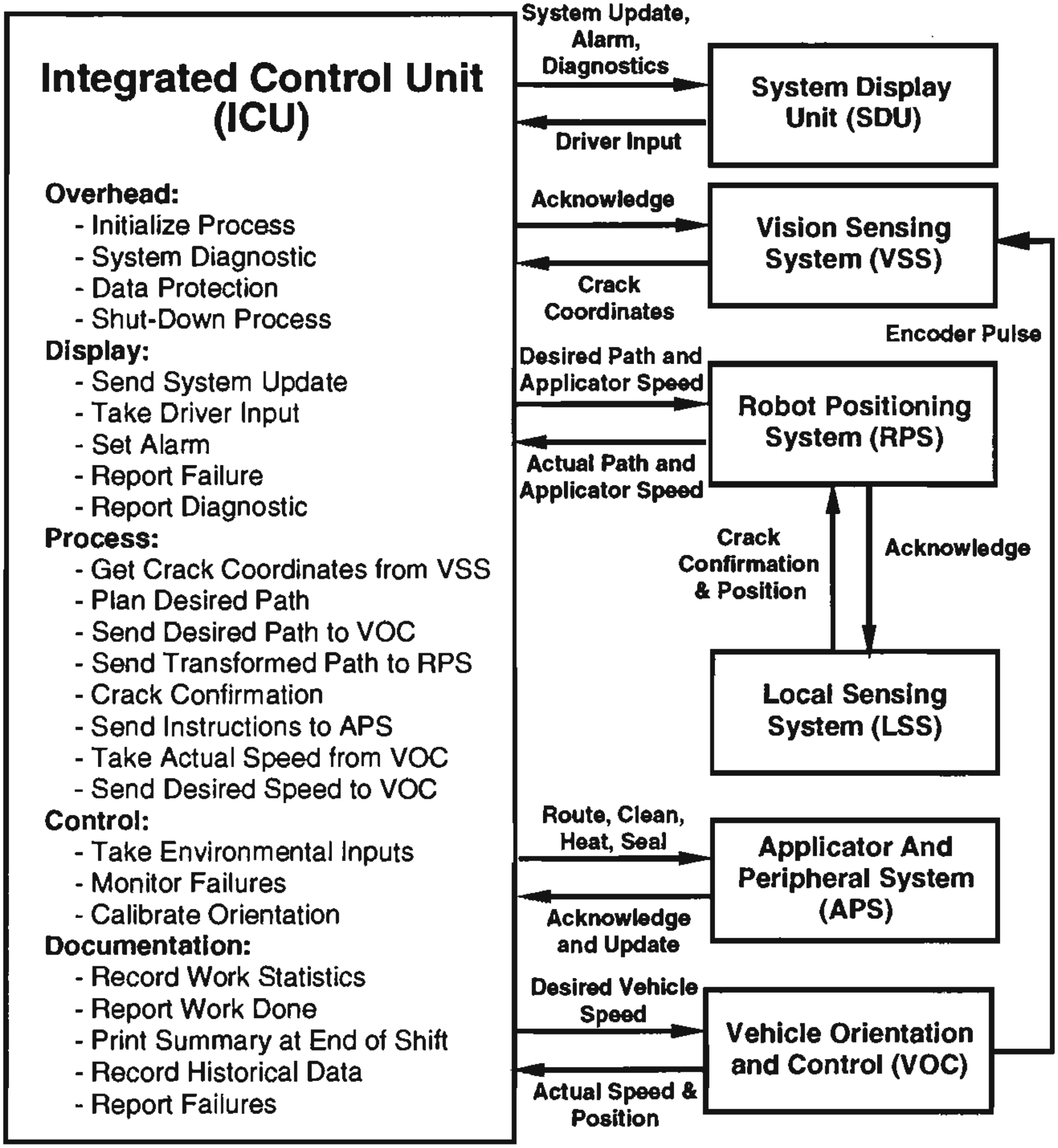


Figure 1.1 - Crack machine system architecture.

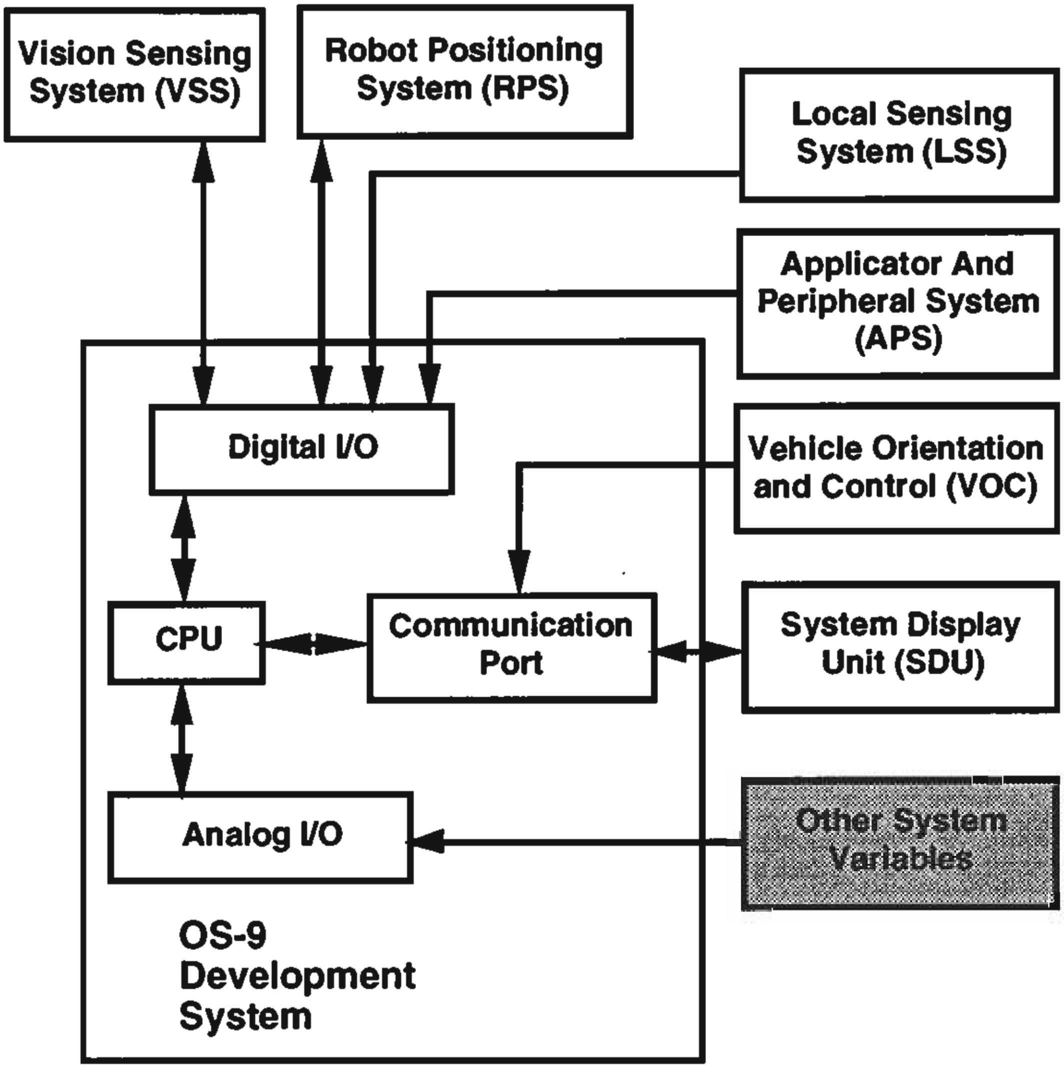


Figure 1.2 - **Integration and Control Unit block diagram.**

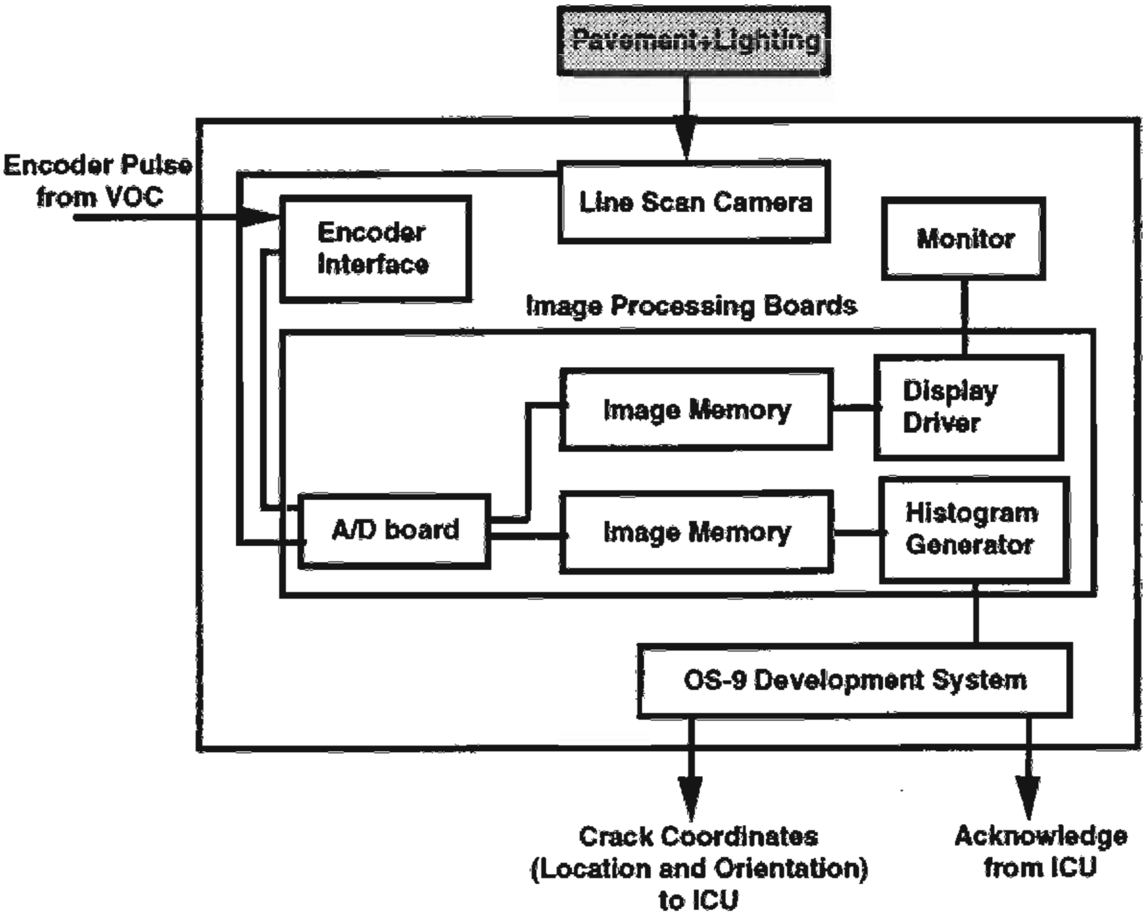


Figure 1.3 - Vision Sensing System block diagram.

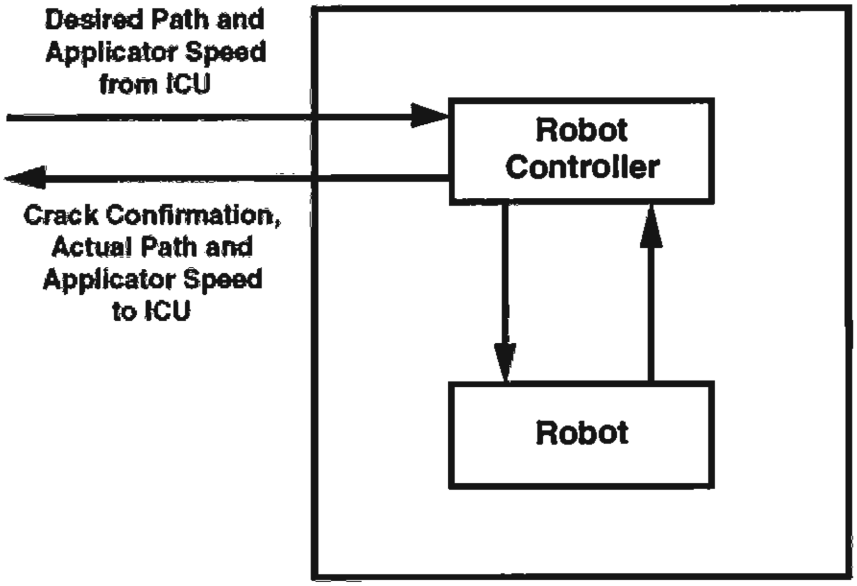


Figure 1.4 - Robot Positioning System block diagram.

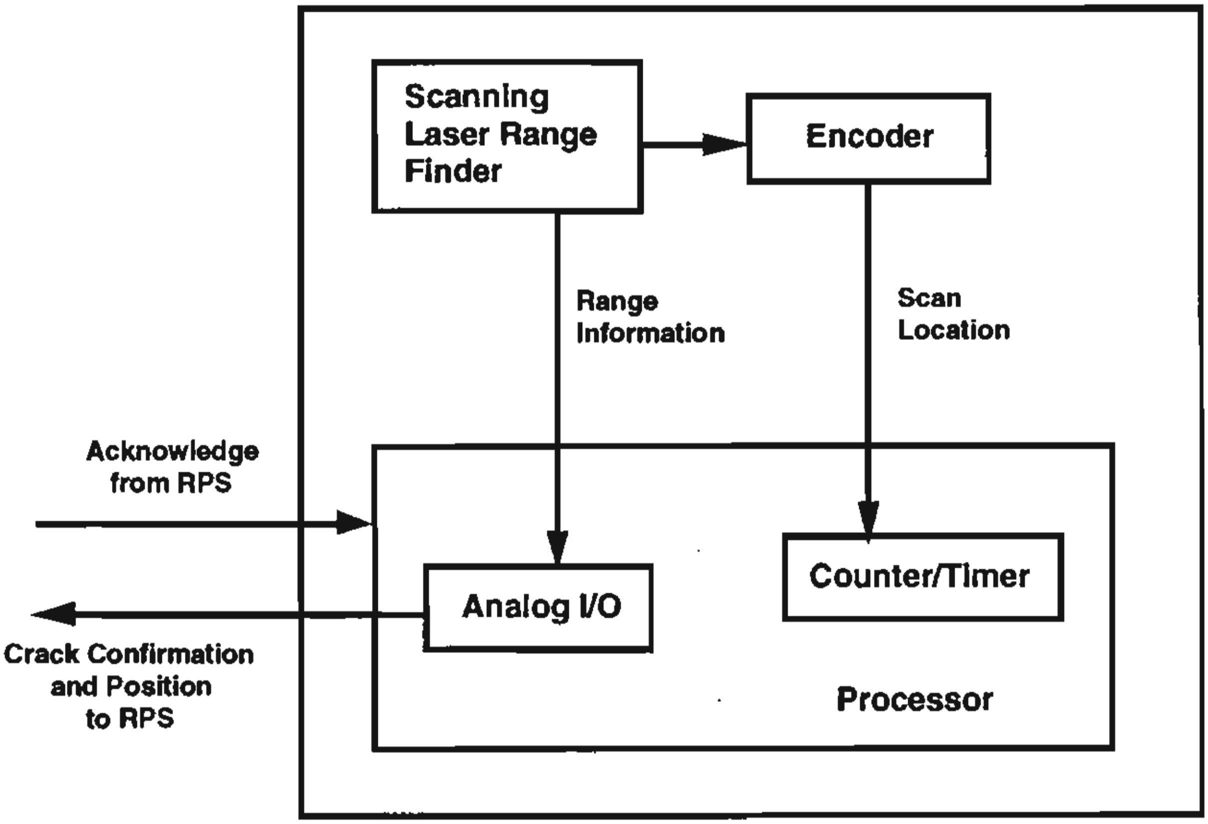


Figure 1.5 - Local Sensing System block diagram.

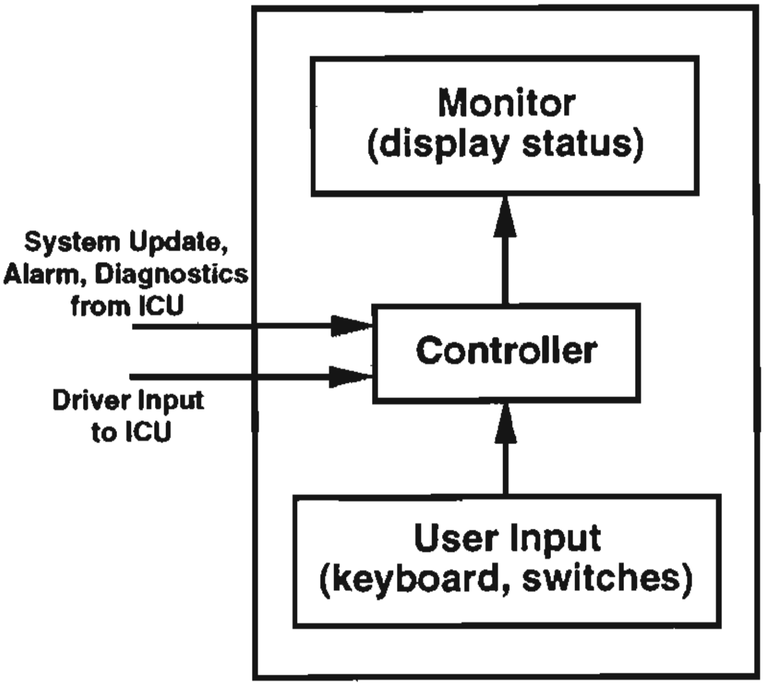


Figure 1.6 - System Display Unit block diagram.

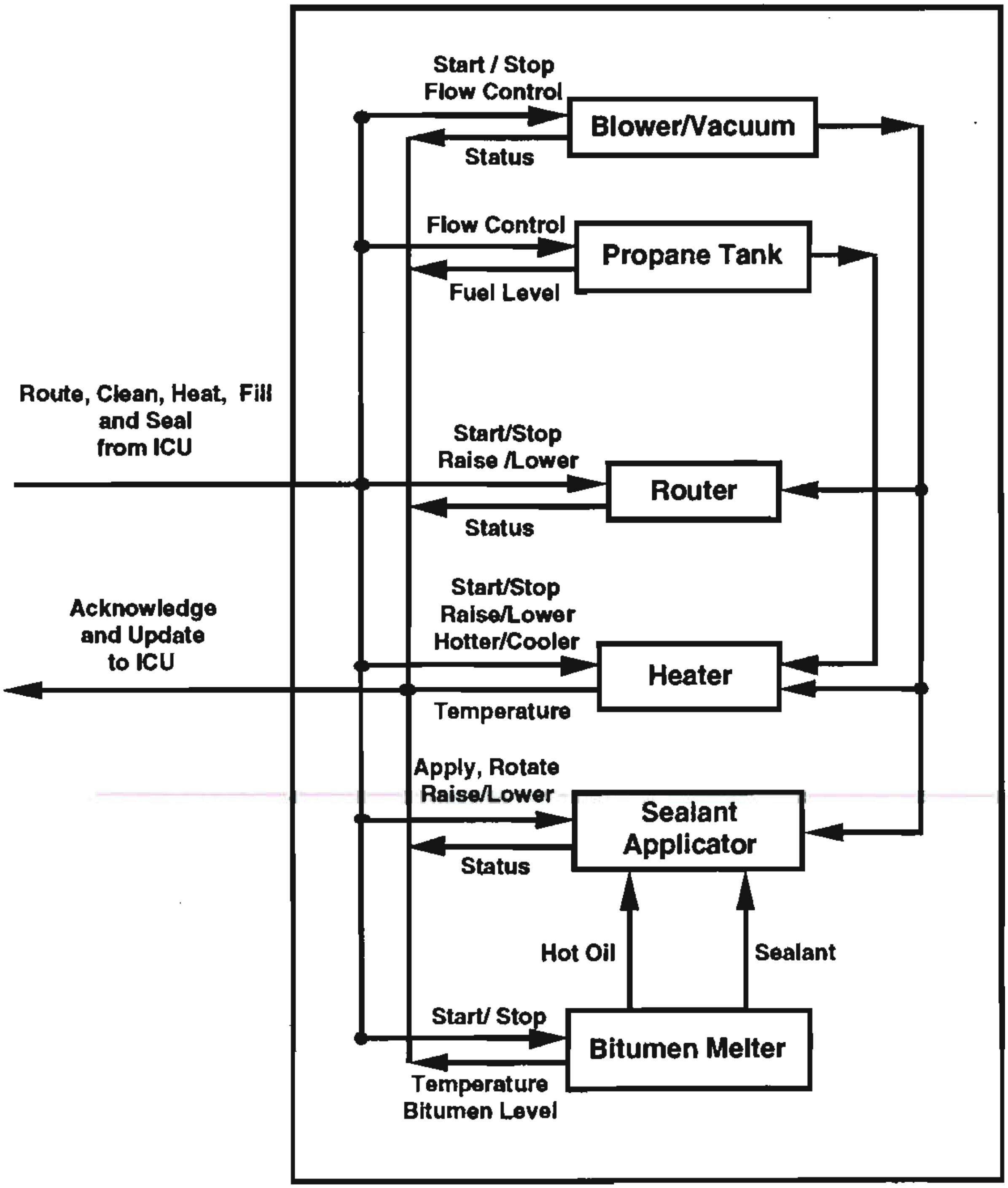


Figure 1.7 - Applicator and Peripherals System block diagram.

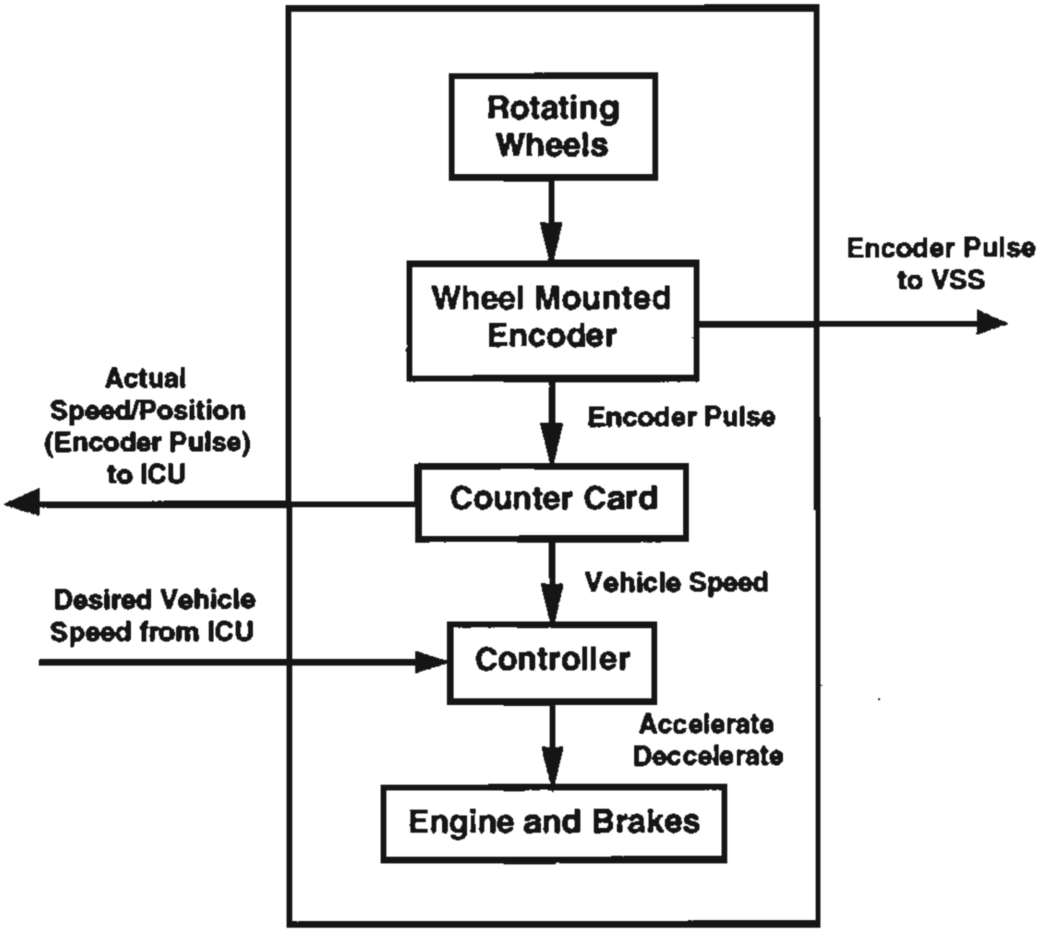


Figure 1.8 - Vehicle Orientation and Control System block diagram.

1.4 - Machine Concept

Early on in the machine development process (when the original proposal was being developed) and based on the two types of cracking that we intended to address, we promoted the development of two independent machine systems, one for longitudinal cracks and joints that exist at the edge of the lane (construction joints, etc.) and the other for general (random or transverse) cracks/joints that may extend across the full lane width. However, many of the same major components would be necessary for each machine such as sealant melters, hydraulic power supply, etc. Thus, it become quite apparent that a dual purpose machine with a portion to address longitudinal cracks and another portion to address general cracks was quite logical and would present a significant economic advantage in terms of capital investment for potential highway agency users. The primary difference between the two crack sealing components is due to the positioning system as many of the same parts are utilized in these two portions of the machine. To follow, we discuss in a general manner, the differences between the two machine component positioning systems developed.

The development of a machine to automatically seal or fill cracks of sometimes arbitrary geometry is quite challenging. The primary challenges arise from:

- The number of degrees-of-freedom required to follow an arbitrary crack,
- The required unsteady operation of many of the components.

Furthermore, the support vehicle must provide the continuous movement of the machine at extremely slow speed which is difficult to perform.

A machine to perform the longitudinal operations has several different requirements including:

- Fewer required number of degrees-of-freedom to follow longitudinal joints and cracks,
- Considerably different sensing requirements, and
- The steady-state operation of many of the components.

Furthermore, for the simpler longitudinal operations, the use of the support vehicle to provide a continuous movement of the machine is relatively easy. As such, the positioning system concept for the longitudinal portion of the machine is significantly simpler than the general machine.

Figure 1.9 is a computer rendition of the initial machine concept developed. This concept has been animated early in the project and a video of this animation has been used extensively to demonstrate the operation of the machine.

The general crack sealing operation takes place off the rear of the vehicle. In order to provide for crack following capability, commercially available robots mounted on linear slides were initially proposed. Since robots generally have poor strength to weight ability, tool carts support the end-effectors, and the robot system is only required to position these tool carts and move them along the crack.

The longitudinal positioning system relies on hydraulic positioning of a simple linkage supported off the side of the support vehicle. The system is designed in such manner that the weight of the end-effectors are supported by a support frame mounted on casters, and the casters provide positioning of the end effectors relative to the roadway. The routing, heating/blowing, and dispensing end effectors are all supported by the same frame as is the local sensing system. The positioning system provides motion of the frame normal to the direction of vehicle motion. Placement of this part of the machine allows it to be easily stowed for travel to and from the job site. This design was chosen for ease in fabrication with many commercially available components.

This section of the report desires only to illustrate the initial machine concept selected. Details of the integrated machine and the positioning systems will be discussed in much additional detail later in this document. However, we would like to stress the critical aspects of the overall machine development plan which include:

- The use of two main machine systems to address longitudinal cracks and general cracks independently. This has allowed for on-road testing of numerous components within the longitudinal machine, while the general machine is still in development. Also, this provides for a means of phased commercialization, starting with the simpler and less expensive longitudinal machine.

- Modularity - the use of stand alone subsystem components and the use of identical components in both machine systems. This has allowed for the independent development of components, the ability to tailor the machine to each end-user's crack sealing method, and a minimal parts inventory necessary.

- The incorporation of feasibility testing into first generation component testing whenever possible. Primarily, this has allowed for the expedited development of the machinery.

- The use of commercially available components whenever possible. This has provided for the expedited development of the machinery in addition to higher component reliability.

We believe that these critical factors have allowed for the successful development of the integrated machinery in the short duration of this project.

1.5 - Report Summary

This document is the Final Report of SHRP H-107A: Fabrication and Testing of Maintenance Equipment Used for Pavement Surface Repairs. Phase I of this project involved a detailed feasibility study, creation of a machine development plan, development of an integrated machine concept, and the design of first generation machine components. A final report at the end of that phase details all of the noted items. Phase II involved the fabrication and testing of the first generation components which led to the development of second generation components. A two part final report discussed details of these activities.

This document reports on the prototype integrated machine developed, in addition to the final components used. In Chapter 2, detailed second generation component descriptions and discussions on the principles of operation of each of the machine components and subsystems are presented. Engineering drawings of the various components have been included along with photographs of the manufactured components. These drawings and photographs are primarily contained in the Appendices which also contain the vendor specifications for much of the equipment purchased. Performance specifications of the components are also discussed.

Chapters 3 and 4 discuss the integrated longitudinal and general crack sealing systems, respectively. The important features and the coordinated activities of the numerous components are emphasized. Chapter 5 discusses the testing of the integrated prototype machine including the test plan, test results and corresponding machine performance.

Chapter 6 concentrates on commercialization issues of the integrated machine. This includes machine cost projections and cost benefit analysis, in addition to recommended machine modifications that will allow the machinery to address all types of crack and joint sealing/filling operations. Chapter 7 presents ideas as to how the automated machinery could be integrated into the maintenance programs of highway agencies. Finally, Chapter 8 summarizes the conclusions and recommendations of this project.

Figure 1.9 - Integrated machine concept.

2

Second Generation Machine Components

2.1 - Integration And Control Unit (ICU)

2.1.1 - Introduction

The development of an Automated Crack Sealing machine (ACSM) includes the integration of a variety of sensing, command, and actuating systems, many of which will synchronously perform tasks in real-time. A control architecture has been developed to assure that these systems act in a coordinated manner to achieve the overall goal of sealing pavement cracks at an acceptable performance level. It is important to note that control system architectures have the definitive purpose of ensuring that a task is achieved and correcting for any deviations affecting the execution of this plan. From a technical standpoint, the control architecture requires a modular configuration in order to profoundly affect the versatility and maintainability of the resulting product. There is also a direct connection between the control architecture and design time, integration and overall functionality of the product. Furthermore, from an industrial standpoint, architecture choices are commercially important in the production costs and marketing appeal considerations. In short, the choice of the control architecture for a particular product can have a profound affect on the development as well as the commercialization of that product.

During the Phase I feasibility study, it was determined that the Integrated Control Unit (ICU) of the Automated Crack Sealing Machine oversee all operations from start to finish. This control unit needs to coordinate and initiate information and control flow between the separate systems of the machine. The ICU, therefore, acts as a liaison between the otherwise disassociated systems. In addition, the control system must perform efficiently to sustain ACSM operation at the required speeds.

Specifically, the ICU must take crack location information from the Vision Sensing System (VSS) and use Vehicle Orientation and Control (VOC) system information to translate that path into a form usable by the Robot Positioning System (RPS) and valid for the current reference frame. Thus, the ICU will accommodate path planning and updating algorithms necessary for accurate crack/joint sealing/filling. The ICU will also interact with the Applicator and Peripherals System (APS) in order to synchronize applicator positioning and usage.

In review of the machine requirements, it is apparently necessary for the ICU to meet the following criteria:

- fast and efficient computation
- able to recognize and process prioritized interrupts
- process concurrent information rapidly (multitasking)
- retain sufficient spare capacity and flexibility to expand
- support multiple processors
- expandable backplane

In addition to these necessary requirements, other development requirements were recommended as follows:

- modular in both hardware and software design
- application software should be developed in a user-friendly environment that is common to many programmers
- system software should be ROMable to enable an embedded application
- vehicle mounted ICU needs to be rugged to operate in a hostile environment (the environment as described in the Phase I report)
- compatible with other Caltrans/UCD in-house development efforts and expertise

Considering the responsibilities of task monitoring as well as the development requirements, the ICU team assessed, recommended and purchased a "mother system" for the crack sealing machine and acquired a development system. Based on compatibility with other subsystems, ruggedness, bus transfer rate, multiprocessing capability, and compatibility with other highway maintenance automation projects, the Single Board, Smart I/O, STD Bus, PC/AT, and MultiBus options were eliminated. The VME system bus architecture utilizing the OS-9 real-time operating system was selected as the most desirable based on all considerations and requirements. The VME bus provides the highest bus transfer rate, is rugged enough to perform in the maintenance vehicle environment and is a truly flexible system. The VME bus provides the flexibility, compatibility, modularity, and multiprocessing necessary for the efficient operation of the ACSM. OS-9 was recommended as the operating system for the VME bus because it is increasingly accepted as a standard and complies with the requirement to be compatible with other ACSM subsystems and other Caltrans and UC-Davis automated highway maintenance projects.

2.1.2 - The Development Environment

A Sun SPARC II workstation has been used as the development system for the ICU software, since it provides the user-friendly programming environment required for a development system. This workstation has been loaned to the project by Caltrans and is used only for ICU development; the final ICU will not employ this workstation, only the VME hardware. The Sun workstation is connected to the VME system (target system) via an Ethernet backbone. The Sun workstation combined with the VME system is referred to as the 'development environment' and serves as the programming environment when connected via the 'telnet' command. Using the VME system terminal, only one process, such as editing a program or executing code, can be run at once. In using the Sun workstation development system, however, multiple windows and multiple tasks are accommodated. Thus, several windows and processes can be open and running on the workstation. In this manner, the programmers can edit a program in one window while another program is compiling in another window and, perhaps, even executing through another window. Therefore, many processes can be executed at once, allowing for quicker program development and accurate testing of the multitasking capability of the VME system. Since it is connected to the VME system via Ethernet, the Sun workstation also serves to simulate the Vision Sensing System (VSS).

In order to provide a user-friendly graphical interface, the RAVE (Real-time Audio Visual Environment) system was added to the system recommended in the Phase I report. The RAVE system, with software developed by Microware, Inc. and hardware developed by Vigra Corporation, is designed to allow development of a graphical user interface. The RAVE software provides a library of graphics, representing dials, meters, buttons, etc., and allows the programmer to create an interactive operator screen. RAVE generates the resulting code for the graphics portion of the interface, while the programmer adds the code to be executed upon user interaction. For example, the programmer can specify that a red and black vertical meter be placed on the interactive screen in a certain position; RAVE will generate the code to recreate this graphic image; the programmer can then add code to cause the vertical meter to move according to certain input. In this manner, a complete user interface screen to serve as the "Crack Sealing Machine Control Panel" is easily defined and developed. In this manner, an Input/Output simulation program has been developed.

2.1.3 - Detailed Components Description

The components of the ICU are of two types - hardware and software. During Phase II some hardware components were added and several software components were developed. These components were developed individually and then integrated to form the ICU. Following is a current list of ICU components with detailed descriptions of each. Appendix A contains manufacturer's specifications for many of the items discussed below.

2.1.3.1 - Hardware Components

Backplane (HSE/17R-12V-W60-F3-S150-Ethernet Cables)

The backplane integrates all the cards of the ICU. It includes a 17.5 inch (height) rack mount enclosure with 12-slot VME card cage, 500 Watt power supply, 60 MB Embedded SCSI hard disk drive, 2 MB 3.5" (38W7 format type) floppy disk drive, 150 MB 1/4" Archive Streamer Tape Drive and Ethernet Cable Package which includes an Ethernet Transceiver, Transceiver cable, 10ft. Thin Net Cable, T-connector (Thin-Net) and 2-Terminators (Thin-Net).

CPU Card (HK68H/V3E-4 MB)

Includes a 50 MHz 68030 CPU with 4 MB DRAM, 128 bytes non-volatile RAM, 4 RS-232 ports, single parallel port, VSB compatible bus interface, SCSI interface, time of day clock and full interface to VME bus with four level system controller functions.

Analog I/O Card (XVME540)

Analog I/O card. 12-bit A/D and D/A conversion. 16 channel, 4 channel output. Inputs configurable to bipolar or unipolar with 12-bit conversion resolution.

Digital I/O Card (XVME201)

Digital I/O card. VME bus interface, two 68230 Parallel Interface Timer (PI/T) chips, and TTL buffers to provide 48-bits of digital I/O. 4 bi-directional 8-bit ports and two 16-bit ports.

Communications Card (CMC ENP-10)

Ethernet communications card. Interface between VME bus host system and Ethernet. Processes network protocols, manages the local bus and performs DMA transfers across the bus.

Multi Media Graphics Card (MMI250)

Hardware component of the Real Time Audio Visual Environment (RAVE). A high performance graphics board for the VME bus that combines graphics frame store, keyboard, RS-232C, and sound output functions to provide an effective man-machine interface. It is a standard 6U board with both VME bus and VSB bus interfaces, and provides a bit-mapped color graphics controller, an IBM/PC compatible keyboard interface, two RS-232C compatible serial ports, and 4 MB of multi-ported frame store RAM. The MMI250 provides the hardware necessary to run the user interface screen, keyboard, speaker and the graphical processing required for real time display of information.

Test Box

A Test Box was designed and developed to provide and take digital and analog signals. These signals were used to simulate input and output information coming into and going out of the ICU. Functions of the test box were displayed on the user interface and control of the test box hardware was accomplished using the user interface.

Connection Box

A Connection Box was designed and built to provide a clean connection point between various peripheral lines/wires and the ICU's input/output ports. This box has a side where all input/output wires, bundled together, enter the box. Within the box, there may be signal conditioning devices to eliminate noisy components of desired signals or to boost the signal strength. Also within the box, all wires are terminated to a connection bar. The connection bar accommodates the ribbon cables connected to the ICU. Here, the wires from the peripheral systems are assigned to their expected port bits or analog port wires. This box provides a focal point for signal troubleshooting, as well.

2.1.3.2 - Software Components-Basic System

Software modules developed by the team are typically generic. This simplifies the task of interfacing with other subsystems of the crack sealing machine. Integration will require only minor modifications to software modules.

Operating System (OS-9 Professional)

Real time, multi-user, multitasking operating system with a system state debugger and a source level debugger.

Software Drivers (ENP-10 and VXME982)

Software drivers for Ethernet and I/O cards with all requisite libraries.

Real Time Audio Visual Environment (RAVE)

A graphical user interface development package which can be customized for a specific application. This has the capability to provide real time machine control and to provide real time user feedback.

2.1.3.3 - Software Components-System Test Modules

The following modules were developed to test the I/O cards and to develop multitasking capabilities:

analogio.c	initializes the analog I/O board(XVME540) and reads analog input signals from input channels.
anrave.c	a modified version of analogio.c to work with RAVE.
diotimer.c	tests the functionality and initializes the digital I/O board.
demo540.c	tests the interrupt generating capability of the analog I/O board (XVME201).
proc1.c	tests the multitasking capabilities of OS-9 operating system. In particular, tests the signal and pipe mechanism while running concurrent processes.
icurpscom.c	Sends path information of the crack to the Robot Positioning System (RPS) over the serial communication port. Receives two types of data from the RPS, i.e. signals indicating the current status of the RPS and the current location of the end effector. In case of errors it sends a new planned path to the RPS.

2.1.3.4 - Software Components-Data Modules

icu.data	disk based crack configurations generated by the Vision Sensing System (VSS).

2.1.3.5 - Software Components-Communication Modules

The following modules were developed to test the communication cards and to develop data transfer capabilities on the Ethernet network:

comdraw.c	receives crack information from the Vision Sensing System (VSS) and displays it on the user interface.
drawarray.c	displays crack information obtained from magnetic media(disk)
hold.c	a network driven interrupt handler to facilitate processing of information exchange on the Ethernet.
send.c	a module to send data from icu.data to comdraw.c over the Ethernet network.
icureq.c	This program makes a request to vision system, actually the request is made to visionhold. Visionhold interrupts visionstub through a pipe "/pipe/hv". Visionstub handles the signal and replies vision data through "/pipe/vh" to visionhold. Visionhold picks up these data and sends them to icureq.

2.1.3.6 - Software Components-Main Module

acsm.c	This program integrates the above mentioned Test, Data and Communication modules. Various sub modules are utilized by acsm.c. These include graphics generators, mouse and keyboard facilitators, sound generators communication subroutines. The program also forks out a process to the path planning subsystem.

2.1.3.7 - Software Components-User Interface Module

Buttons:	vrsbut.c, hydrbut.c, routr.c, slbut.c, comprbut.c, glowbut.c, lpsbut.c, gnrbut.c, starbut.c, sealbut.c, stopbut.c.
Overlay windows:	statsovl.c, crwinovl.c.
Indicators:	mltmtr.c, mltrmtr1.c;

Screen: acsmscr.c.

2.1.4 - Description of Tasks

Five distinct ICU tasks are as follows:

1. System diagnosis and initialization
2. Data communications with other ACSM subsystems
3. Input/output with machine hardware
4. Operator machine control and monitoring via user interface
5. ACSM information flow and control.

The task of system diagnosis and initialization would be conducted at the beginning of a crack sealing run. Initialization clears any control lines and resets them to an initial setting. ICU input/output boards are reset to accept and place information on the 'correct' lines using an expected format. Other dependent systems are also reset and prepared for communication. Any system and/or subsystem problems are identified and corrected, if possible, in this stage. The initialization routine for the ICU is executed by several independent routines: analogio.c or anrave.c, diotimer.c, demo540.c, proc1.c, and system.c. These routines specifically initialize and diagnose the XVME540 (Analog I/O), XVME201 (Digital I/O), and HK68H/V3E-4 MB (CPU) boards of the ICU. In the future, the initialization and diagnosis processes will be incorporated into one independent routine.

The task of communicating with ACSM subsystem refers to Ethernet communications through the ENP10 Ethernet board and backbone and to RS232 communications through the serial port. Ethernet communication will be used with the Vision Sensing System (VSS). Data from the VSS is sent over the Ethernet network to the ICU. The ICU waits for the data and displays it on the user interface whenever it is transmitted. The ICU displays a window once a data transmission begins and closes it after data transmission is complete. The socket.c, comdraw.c, drawarray.c, hold.c, and send.c routines facilitate the task of communication over the CMC ENP-10 (Ethernet) board. Data exchange between the other sub-systems will be implemented via a concept of shared memory. This memory can be accessed in real-time by the sub-systems which need to use the shared information.

The ICU communicates with the Robot Positioning System (RPS) through the serial port, 't2'. Information about crack locations is passed to the RPS; information about status of finding and/or following the specified cracks is passed back from the RPS to the ICU. The communication between the ICU and RPS is transparent to the user unless the RPS doesn't find a crack where it was specified. In this case, the user is notified about the search routine in progress and about its success. The status of the RPS' success and progress is continually transmitted back to the ICU via the duplex serial communication. The ICU transmits crack location data to the RPS when the current frame of data has been updated following the RPS-initiated search routine or when the truck has moved forward, stopped, and the operator has specified that a new workspace is ready to be sealed.

The ICU also receives information from the Uninteruptable Power Supply (UPS) over another serial port. Only information about time left with power in emergency situation (generator off) will be transmitted to the ICU over this line.

Subsystem input/output includes information passing through the analog and digital boards. This task handles the subsystem control and/or monitoring not handled through the Ethernet or RS232 links. An example is the control of various subsystems of the Applicator and Peripherals System (APS). The operator is able to watch the 'health' of the ACSM through the graphical user interface provided by the ICU. (This user interface is described in the following paragraph.) The sensor wiring terminates in the connector box described in the Hardware Components section 2.1.3.1 and the digital and analog boards access the peripheral signals at this box. The following is a list of peripheral signals available to the ICU:

(IN THE FINAL REPORT, IT WILL BE STATED WHICH ARE ACTUALLY MONITORED AND/OR CONTROLLED BY THE ICU.)

<u>Melter</u>

propane pressure
sealant temperature
oil temperature
flame out

<u>Sealant Applicator</u>

sealant level
applicator position
rotation
sealant supply

Heating and Cleaning System

- road temperature
- system on/off
- divertor control
- blower on/off
- heater exhaust temperature
- system failure
- propane level

Router

- on/off
- up/down

Vacuum System

- on/off
- vacuum pressure
- filter pressure loss

Hydraulic Pump

- solenoid status

Generator

- ammeter
- engine temperature
- on/off

Longitudinal Positioning System

- on/off hydraulics
- on/off system
- controller output (status)

Air Compressor

- pressure
- on/off pump

Communication to these peripherals is handled by routines within the main module, main.c, as described in the Software Components section 2.1.3.6.

The user interface allows control of the machine and displays the status of the ACSM in real-time. The following diagram is the basic user interface screen. The crack window (item 1) will show graphical data about the cracks within the current workspace of the robot. In the status window (item 2), the operator will see messages regarding the status of the operation. After the operator clicks on one of the peripheral buttons (items 3), a smaller window displaying the status of that peripheral pops up. GRAPHICS OF THE SMALLER WINDOWS WILL BE PROVIDED FOR THE FINAL REPORT. In this secondary window, the operator may also provide some control of peripheral system parameters. Only one of these secondary windows may be open at one time (with the exception of the melter window (item 4), which is continuously open). Also, this window covers the area previously taken by the peripheral buttons only; in this manner, the information on the remainder of the screen will still be visible to the operator. The buttons in the lower left portion of the screen (items 5) allow the operator to indicate to the system when an operation will begin, when the truck has stopped and sealing can safely commence, and when the operation should be stopped. The VSS data will not be processed until the START button is pressed; the RPS will not be prompted until the SEAL button is pressed; and the operation will continue until the STOP button is pressed.

Information flow within the ACSM is controlled by the ICU. Specifically the crack data is obtained from the VSS at the right phase of the operation of the machine and transferred through the Path Planning and VOC subsystems before transferring it to the RPS at the appropriate time.

2.1.5 - Subsystem Interaction

The following diagram, Figure 2.1.1, provides some insight into the current ICU architecture and information flow from other subsystems. This information is based on integration discussions between the ICU and various subsystem groups.

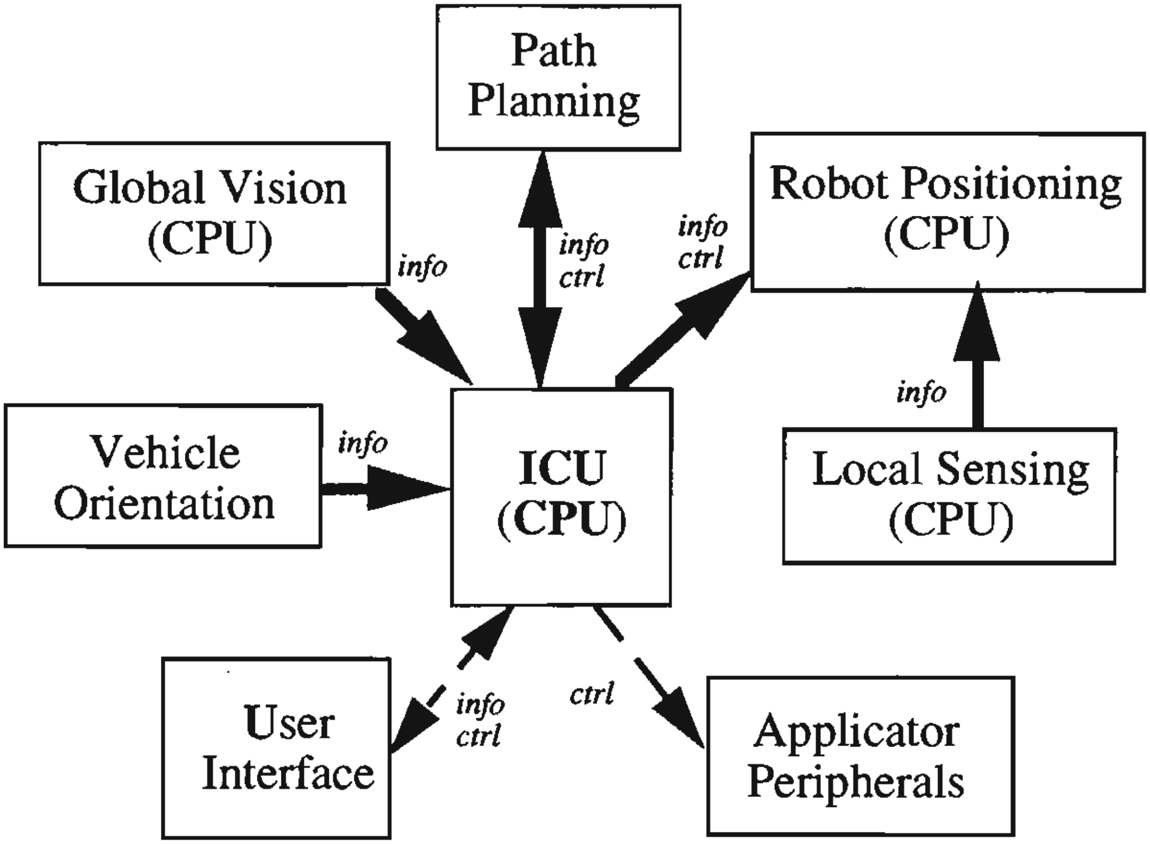


Figure 2.1.1 - **ICU functional architecture, minor links are not shown.**

User operation of the ACSM

At the beginning of a 'shift', or sealing operation run, the operator would turn on the main power to the computer system. The ICU will boot up and automatically run the ACSM User Interface Program. The operator will, then, be prompted to enter the mode of operation (longitudinal crack sealing or general crack sealing) in order to begin. The ICU will inform the operator to wait while the machinery is being turned on and warmed up. Machine control will be initiated by the ICU and hard-wired relays. After the support system is ready for sealing operation, the operator will be notified and an indicator will show the driver that sealing operation is ready. During the operation of the ACSM, several points are valid:

The driver will be notified of maximum speed allowed at any particular time. METHOD OF NOTIFICATION WILL BE DESCRIBED IN THE FINAL REPORT. During sensing , 2mph is maximum speed. During sealing, the vehicle must be stopped.

The START button is pressed by the operator when in a crack treatment area and the VSS is sensing for cracks. The SEAL button is pressed by the operator after the driver has completely stopped the vehicle motion. Following the SEAL command, the ICU will communicate crack coordinates to the RPS for sealing. The STOP button is pressed by the operator when cracks should no longer be sensed. Following the STOP command, the operator will be prompted to enter whether the whole operation is done and shutdown can commence or the operation is only interrupted and the machine should remain ready to START again.

At any time during the operation, the operator may query the status of various support components, as mentioned in the Description of Tasks section above.

2.2 - Vision Sensing System (VSS)

2.2.1 - System Description

The purpose of the Vision Sensing System (VSS) is to locate pavement crack positions using machine vision. This section describes the functional aspects of the VSS. Subsequent sections give a description of the physical system, its components, and how the VSS relates to other parts of the automated crack sealing machine (ACSM).

The VSS consists of two cameras, lighting, an encoder, and a system unit which encompasses image processing hardware and crack detection algorithms. The VSS is to identify cracks greater than .20 inch wide on Portland Cement Concrete (PCC) and Asphalt Concrete (AC) roadways. The VSS processes information from a gray scale image of the top view of a section of pavement, approximately twelve feet wide (one lane width). Acquisition of the image is coordinated with the rotation of the ACSM wheels in order to maintain a proper aspect ratio of the pavement image. Hence, the generation of the image is driven by the forward movement of the vehicle. As the computer acquires sufficient blocks of image data, a ten inch long by twelve foot wide block of video data is built in increments of two inch square tiles. For each of the tiles the determination is made as to whether a crack exists, and if so, in which of eight directions it is oriented. This data is immediately transferred to a remote storage area for path planning, with its position updated from the ICU and Vehicle Orientation and Control System (VOC) as the vehicle continues to move forward. No attempt is made by the VSS to connect indications of crack presence among tiles. This is left for the path planning process. Functional components of the VSS can be seen in Figure 2.2.1. The actual operational steps (single camera shown for convenience only) are shown in Figure 2.2.2.

2.2.2 - Principles of Operation

The most fundamental portion of the Vision Sensing System is the algorithm that determines crack presence. This algorithm consists basically of four steps:

1. Divide the pavement image into a *grid* for which the mesh (tile size) depends on speed requirements, desired resolution, and acceptability of falsely recognized cracks.
2. Build a *histogram* representing each tile.
3. Compute a *statistical moment* of each histogram.
4. *Compare local values* of moments to identify cracks.

We make note that the algorithm makes no attempt to obtain a binary image in order to determine more specific qualities of crack segments through chain coding or other means. To follow is a more detailed description of these four steps.

A video image of the pavement is created with a pixel resolution sufficient to resolve an 1/8 inch feature. In order to satisfy the Nyquist sampling frequency this requires a pixel for every 1/16 inch of highway pavement. A grid is then created to carry information about pavement features contained within tiles (see Figure 2.2.3). Each tile within the grid is represented by 32x32 (1024) pixels. Through the building of a histogram for each tile and a moment computation, the data representing each tile can be reduced from 1024 counts of 8 bit data (8192 bits) to one 32-bit integer representing the statistical moment. This allows quick manipulation of data in order to determine the presence of a crack. The manipulation of the reduced data is further described below.

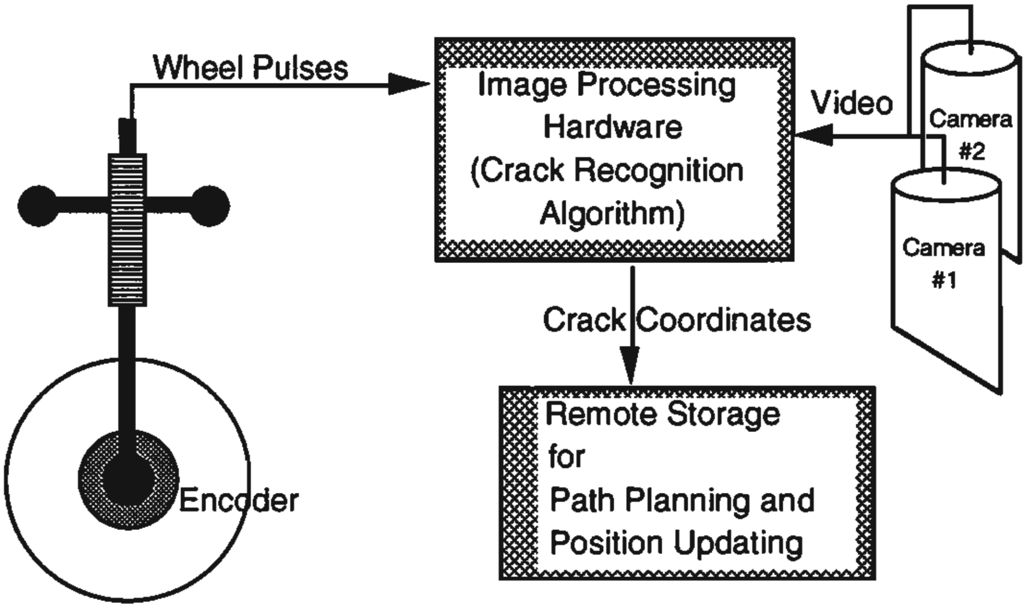
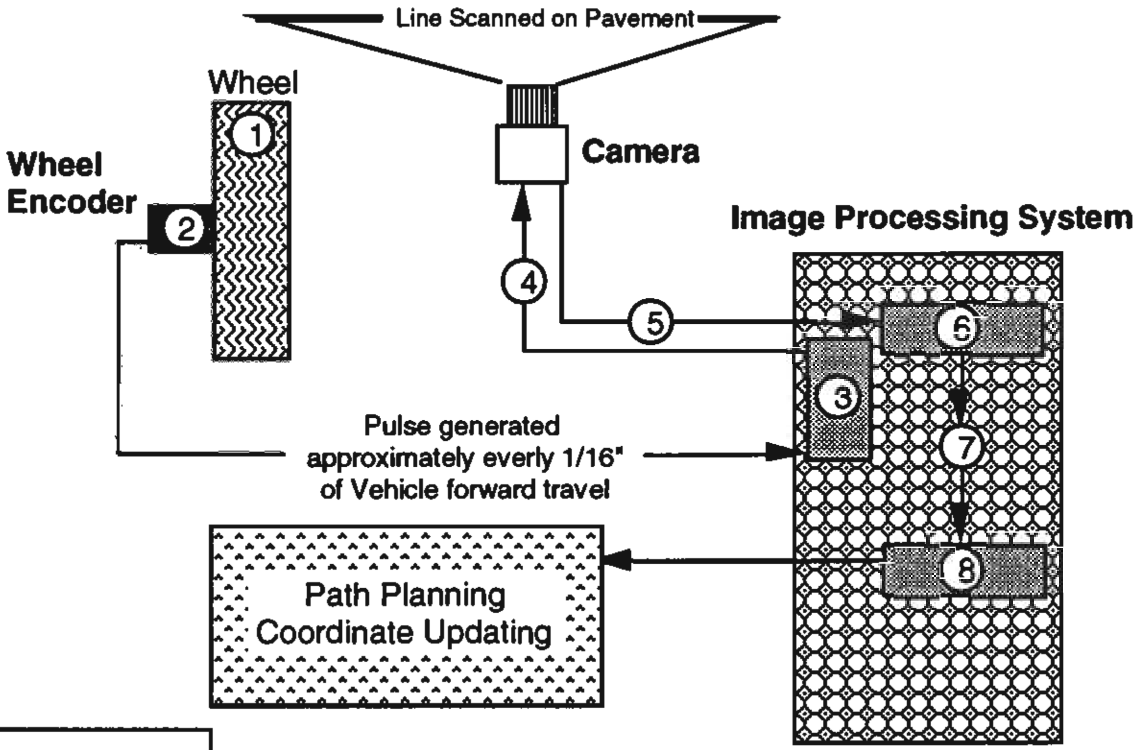


Figure 2.2.1 - Vision Sensing System Functional Layout.



VSS Event Sequence

1. Wheel rotates an incremental amount.
2. Encoder produces a pulse resulting from incremental vehicle travel.
3. Image processing hardware reads pulse from encoder, encoder circuitry filters out vibrations
4. Encoder circuitry sends control signals for camera to acquire video line.
5. Camer returns a video signal representing one line of pavement back to the Image Processing System.
6. Image Processing Hardware procedure iterates until enough lines are gathered to determine crack presence.
7. Algorithm determines crack presence in image (in local areas called tiles) and transmits crack information to communications device.
8. Communications device which sends the crack information to ICU for subsequent path planning and crack sealing (external to vision sensing system).

Figure 2.2.2 - Principles of Operation.

The tile size of 32x32 pixels allows for a minimal variance in local modes by reducing the effects of intensity changes within a tile due to differing shades of aggregate and surface defects without significantly affecting the accuracy required to perform the sealing operation. The small variance in modes allows for a comparable measure of darker gray level values among adjacent tiles. This characteristic of local modes is what specifically allows for the recognition of cracks based on moments about local modes. A local region is defined as a 5x5 grouping of tiles. This is the minimum number of tiles required to identify the eight directions we have selected to recognize.

Next, histograms are created for each tile. A histogram is an ordering of pixel values based on intensities. The number of pixel values that occur in a given area are represented by 256 vertical bars, one for each image gray level (see Figure 2.2.4).

Following the creation of a histogram, a statistical moment is taken about the mode of the histogram for each tile. The mode is the highest value in the distribution. The moment is taken by summing the product of the cubed distance from the mode and the height of the bar for a given intensity value. This is shown in Figure 2.2.5.

Once the moments are computed for each tile, the moment values are compared within independent 5x5 tile grids. See Figure 2.2.3 for four of the eight directions which can occur in this grid. Every tile in the grid (except two tiles on each end) takes its turn as the center tile in the 5x5 area of interest. The comparisons are based on two parameters, the continuity level and the uniformity level. These two parameters determine the extent and the type of comparisons made within the 5x5 area of interest in order to determine the presence of a crack and its direction.

Three crack length selection levels are considered for a crack to exist. These selection levels are called continuity levels. Figure 2.2.6 shows North East bound crack segments and the required continuity levels which will accept or reject a crack based on its length. From Figure 2.2.6 it can

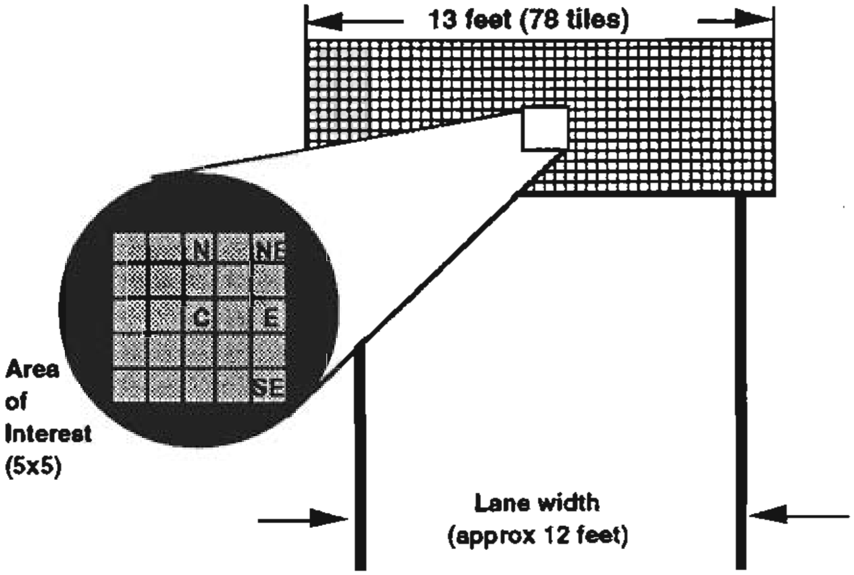


Figure 2.2.3 - Crack directions within 5x5 area of interest.

be seen that a continuity level of 1 requires a crack to occupy only one tile, a continuity level of 2 requires a crack to occupy three tiles, and a continuity level of 3 requires a crack to occupy five tiles. Most of the test results to date have been based on the continuity level of 3.

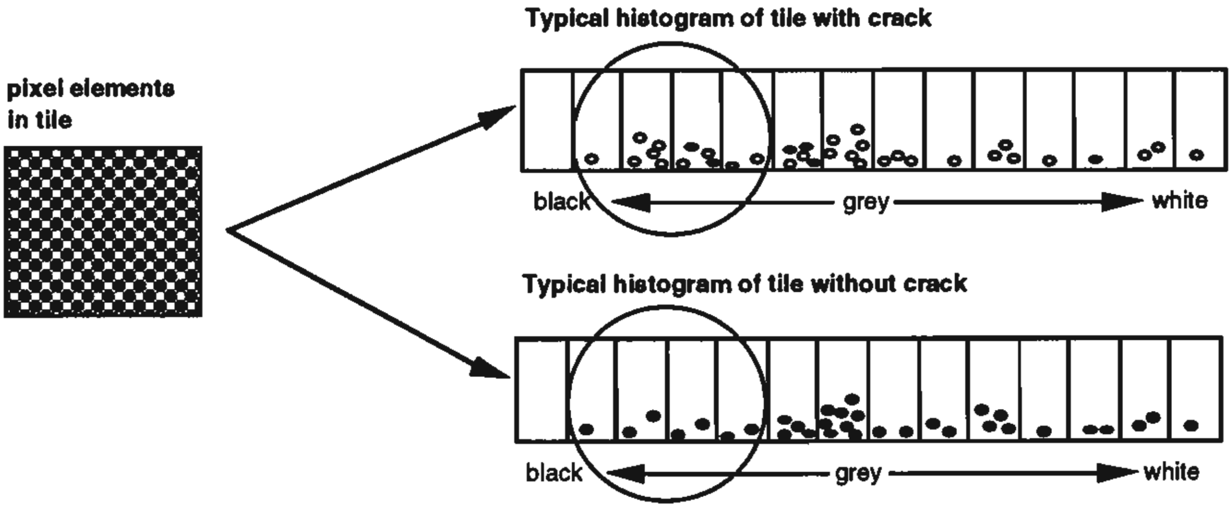
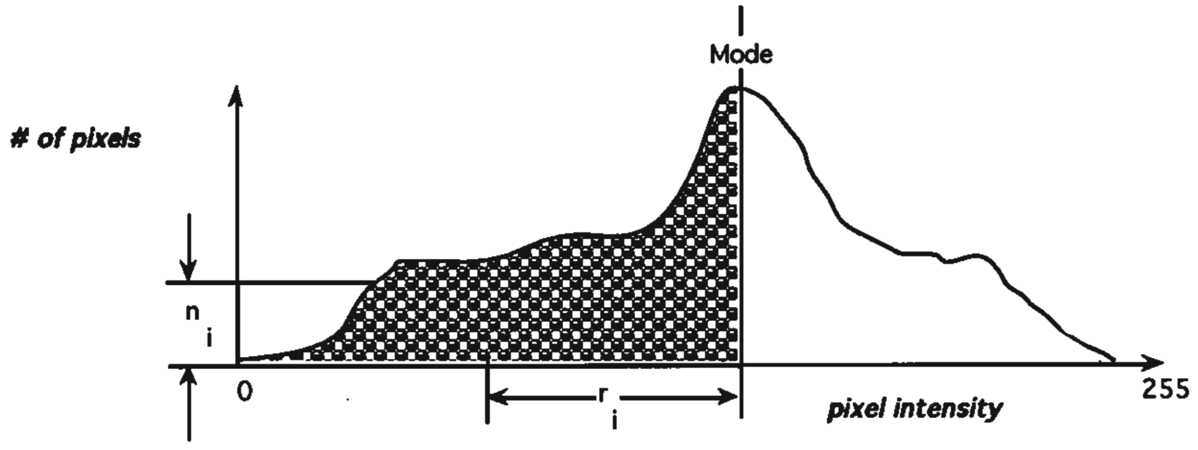


Figure 2.2.4 - **Histogram of cracked and non-cracked tile.**



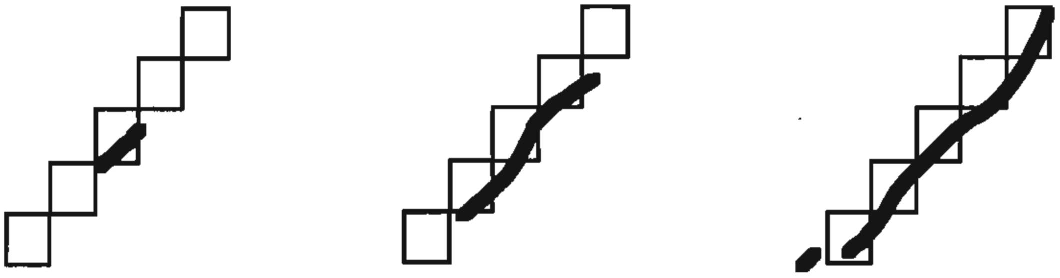
moment = $\sum (r_i^e * n_i)$

r_i=grey level distance from mode

n_i=number of pixels at r_i

e=exponent

Figure 2.2.5 - **Moment Computation.**

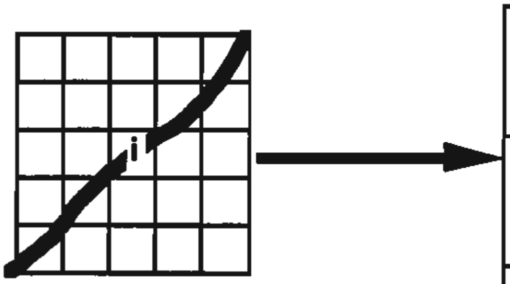


Crack with a continuity level of 1	Crack with a continuity level of 2	Crack with a continuity level of 3
Continuity level 1 **accept**	Continuity level 1 **accept**	Continuity level 1 **accept**
Continuity level 2 reject	Continuity level 2 **accept**	Continuity level 2 **accept**
Continuity level 3 reject	Continuity level 3 reject	Continuity level 3 **accept**

Figure 2.2.6 - Continuity Levels.

The number of neighboring tiles that are used for comparisons in a 5x5 area of interest is called the uniformity level. Figure 2.2.7 shows how these comparisons are made for a continuity level of 2 with a North East bound crack segment within an area of interest. As the uniformity level increases, each tile associated with a given continuity level must be compared to a greater number of neighboring tiles. Note that a crack is recognized at the center tile marked by "i" only if all of the uniformity level comparisons are true. If any condition is false, it is determined that no crack exists for a given direction. The test results to date have been based on using the maximum number of continuity levels for each direction. These comparisons may be optimized with further testing. The continuity and uniformity levels for all directions are shown in Figure 2.2.8.

For a more in depth discussion of the VSS, the reader is referred to the Phase I Final Report and Appendix B of this report which contains company literature describing the wheel encoder, vision system, and cameras purchased.



3l	2lb	4lb		iiir
2la	1l		iir	
4la		i		4rb
	iil		1r	2rb
iiil		4ra	2ra	3r

Example of comparisons:

Continuity level=2 (**i&ii**)

Uniformity level=3 (**1-3**)

Uniformity level 1 check	Uniformity level 2 check	Uniformity level 3 check
i> 1l &1r	**i> 2la &2lb & 2ra & 2rb**	**i> 3l &3r**
iil> 1l &1r	**iil> 2la &2lb &2ra &2rb**	**iil> 3l &3r**
iir> 1l & r	**iir> 2la &2lb &2ra &2rb**	**iir> 3l &3r**

Figure 2.2.7 - Example of comparisons.

3		iii		3
2		ii		2
1		i		1
2		ii		2
3		iii		3

N Comparisons

3	2		iii	
2	1	ii		5
4		i		4
5		ii	1	2
	iii		2	3

N_NE Comparisons

3	2	4		iii
2	1		ii	
4		i		4
	ii		1	2
iii		4	2	3

NE Comparisons

3	2	4	5	
2	1			iii
	ii	i	ii	
iii			1	2
	5	4	2	3

NE_E Comparisons

3	2	1	2	3
iii	ii	i	ii	iii
3	2	1	2	3

E Comparisons

	5	4	2	3
iii			1	2
	ii	i	ii	
2	1			iii
3	2	4	5	

E_SE Comparisons

iii		4	2	3
	ii		1	2
4		i		4
2	1		ii	
3	2	4		iii

SE Comparisons

	iii		2	3
5		ii	1	2
4		i		4
2	1	ii		5
3	2		iii	

SE_N Comparisons

Figure 2.2.8 - Comparisons for eight directions.

2.2.3 - Detailed Components Description

2.2.3.1 - Requirements

VSS performance is judged by the criteria presented in Table 2.2.1.

2.2.3.2 - Lighting

Through a contract to Odetics Corporation, requirements for lighting were determined and a lighting structure was built to optimize intensity and orientation of the lights necessary for proper illumination of the roadway surface to achieve high resolution images. In order to read both transverse and longitudinal cracks, the light falling on the surface should be non-directional. The only true source of non-directional light is sunlight. The goal of the study was to determine which commercially available lighting system would best simulate this non-directional lighting.

Table 2.2.2 shows the comparison of performance for the three most viable white light sources. The fluorescent light is useful in creating a bright light source, but would have to be used in conjunction with a high frequency ballast in order to compensate for the discontinuous light emission (strobe light effect). The performance output level is 2800 lumens per 40 watts, without the ballast. The high pressure sodium lamp has broad spectral content from 550 to 700 nanometers, with the majority of the light (close to 75 percent) between 580 and 630 nanometers, which is a good range for solid-state video cameras. These lamps require a start up time of a few minutes and a ballast. The high frequency ballast for both the fluorescent and high pressure sodium lights can add $200-$500 to the cost of a single unit. For our test purposes, Halogen lamps proved to be the more feasible and cost-effective choice.

A simulation program was written to predict illumination reflected from the pavement and measured by a single camera for different lamp configurations. Based on photometric measurements from a single pair of lamps, the program calculates the light distribution in foot-candles.

RESOLUTION ALONG SCAN/ENCODER PULSE	1/16"
VERTICAL RESOLUTION	1/16"
FIELD OF VIEW	12' 8"
CAMERA DISTANCE TO SURFACE	6'
CAMERAS MUST ENDURE	15 G from 5 Hz to 60 Hz vibration 150 dB noise environment 10% humidity sand & dust salt atmosphere sea level to 10,000 ft. altitude .7 ms exposure time
IMAGE PROCESSING MUST DISTINGUISH	cracks oil spots shadows
CRACK RECOGNITION	.2" to .6" wide >10" length 70% recognition
CONTINUOUS MOVEMENT OF VEHICLE	0-2 mph
CONTROLLED LIGHTING	50% to 75% saturation min. 4500 foot-candles intensity 28" from surface operate and tolerate: direct sunlight rain and freezing conditions
SYSTEM RESPONSE FREQUENCY	18 Hz
SERVICE LIFE	10 yrs

Table 2.2.1 - Vision Sensing System Requirements.

This simulation was exercised to examine a variety of lighting configurations. Illumination was considered for various numbers of lamps and the heights of the lamps from the pavement. The curves shown in Fig. 2.2.9 provide an indication of the variation in illumination as a function of lamp height. Specifically, we are concerned with illumination intensity and uniformity. This simulation considers the full lane width field of view (156 in.) as seen by a single camera located at

SOURCE	OUTPUT	OUTPUT VIS/ALL ($power/cm^2$)	LIFETIME	COMMENTS
fluorescent	2800 lumens/40W	10mW/12mW @2"	12000 hrs	extended, uniform sources
halogen	5000 lumens/300W	.45mW/1mW @10'	1500 hrs	hot lamp
high pressure sodium, clear bulb	15000 lumens/150W	140mW/155mW @4"	24000 hrs	bright light source

Table 2.2.2 - Comparison of Performance for Various White Light Sources.

the center of the left half of that field of view. In the actual VSS, there are two cameras, one in each half of the field of view, and thus we are only concerned with the usable illumination for that camera, i.e. the left half 78 in. Based on symmetry of the VSS, the illumination for the right camera will be the mirror image of the left half 78 in. In general, for a fixed number of lamps, the illumination level will be higher the closer the lamps are placed relative to the pavement. However, there will be a corresponding loss of uniformity in the lighting. Based on the use of this simulation, 7 lamp pairs located at a height of 28 inches from the pavement was selected as the first generation lighting configuration for the VSS testing of Phase II.

2.2.3.3 - Cameras

The cameras require sufficient resolution to consistently recognize cracks .2 in. wide. The field of view transverse to the vehicle is covered by two cameras (Fairchild CAM 1301R CCD Line scan cameras with JML P/N 71846 12.5 mm, f1.3 lenses) mounted 6 feet from the ground. Each camera has a field of view of 6.4 ft. and they are mounted 6.4 ft. apart. Each camera's field is divided into 1024 elements representing .075 in., for a Nyquist resolution of .15 in.

2.2.3.4 - Encoder

The encoder must trigger a line of video every .0625 in. The video acquisition is driven by the forward travel of the vehicle using a 1000 pulse per revolution optical encoder from Datron Technology. The rolling radius of the wheel on which the encoder is attached is 13.25 in. resulting in a pulse every .0835 in. and pixel spacing of .0835 in., in the forward traveling direction of the vehicle. Therefore, the theoretical Nyquist resolution of the image is .167 in. which is 20% better than the .20 in. crack width required of the system.

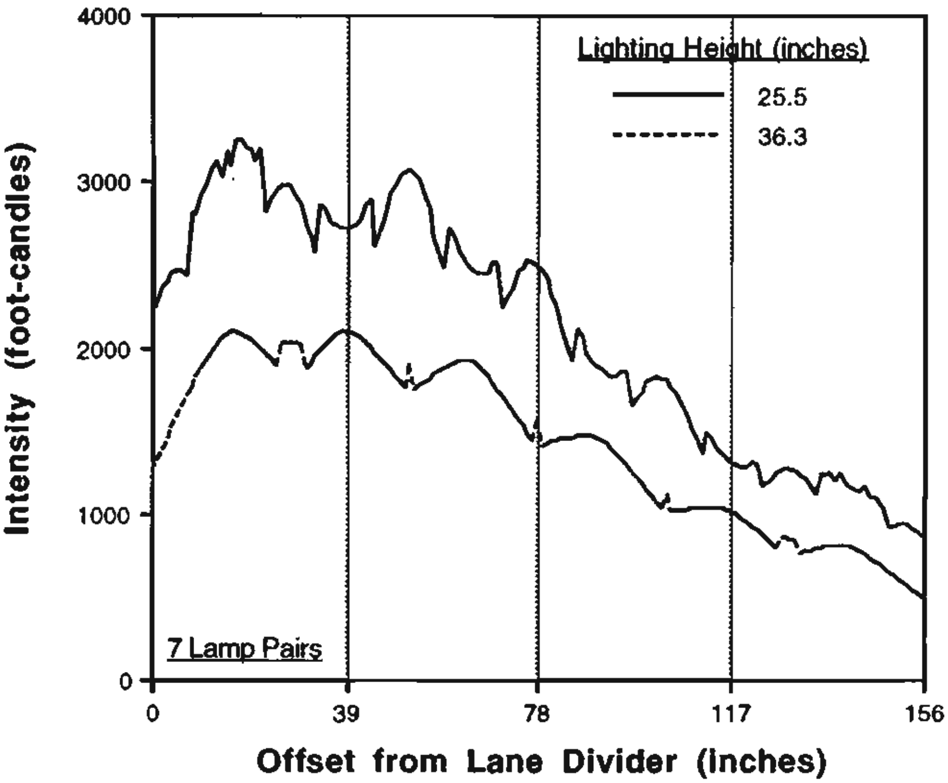


Figure 2.2.9 - Examples of Simulated Illuminations for VSS Lighting.

2.2.3.5 - Image Processing Hardware and Software

In order to produce accurate data for external (outside VSS) processing, the image processing hardware and software must interact efficiently. The encoder and cameras supply accurate data to the image processing boards. Upon a rising edge pulse of the encoder, a line of video from each camera is sent to the MaxScan card. Next, raw data is sent to the ROI 512 and ROI 2048 cards. The ROI 512 processes the data which is transferred to MaxGraph for visual observation. The ROI 2048 utilizes the same data to process pertinent information into FeatureMax MKII for crack identification.

The information for crack identification is implemented with an algorithm which will interpret the presence of a crack by statistical means. The presence of a crack is determined by establishing its width and length. Cracks less than .2 in. wide and less than 10 in. in length are rejected.

Acceptable crack information along with its location and direction are transferred for external processing. Seventy percent of the cracks are expected to be recognized and deemed acceptable. Prior static testing indicates that this algorithm is functioning as expected.

2.2.3.6 - Hardware Components

Two Loral Fairchild CAM1301R Line Scan cameras

The CAM 1301R cameras each divide their field of view into 1024 pixels.

Lighting Frame

Sixteen floodlight fixture hubble, model QL505
Fourteen 500 Watt tungsten halogen lamps (clear)
Phillips ordering code, 500T3Q/CL FCL

Encoder, One DATRON, CORREVIT WPT-4500

Encoder with mounting hardware The encoder has a resolution of 4500 pulses per revolution.
The encoder is attached to the left rear wheel hub on the MIL.

External encoder control circuit

The external encoder circuit was designed in house to:

1. Control the integration cycle of the cameras
2. Provide a means of calibrating the encoder signal in reference to distance traveled.
3. Filter out extraneous encoder pulses due to vehicle vibration.
4. Trigger the Datacube system to collect a line of video in sync with the start of the next camera cycle, after an encoder pulse

Radstone, OS-9 development system

cs-20 2/001 20 slot chassis with
1200W PSU
6 SLOT VSB BACKPLANE
WK-3/300 170MBYTE HARD DISK
Ethernet Card

Datacube image processing system

MAX-SCAN 10MZ
ROI STORE 2048
ROI STORE 512

FEATUREMAX MKII
MAX GRAPH
Manuals

2.2.3.7 - Software Components

Operating System (Radstone Version 5.1, OS-9 Version 2.4)

ImageFlow (DataCube image processing software)

Crack recognition algorithm

2.3 - Local Sensing System (LSS)

2.3.1 - Component Description

The purpose of the Local Sensing System is to locate crack position and measure crack width to a degree of precision such that the crack preparation, sealant application and shaping of the seal can be performed in an automated fashion.

On the general crack sealing machine, the LSS will work in conjunction with the VSS to confirm the presence of a crack within a given area. The VSS will locate the approximate position of a possible crack using a video camera. This camera uses a line scan charged coupled device (CCD) as its sensing element. As the vehicle moves, lines across the lane width will be gathered to form an area view of the road surface. Through measuring the intensity of gray levels which the camera senses, it is possible to determine the position of possible cracks. However, since the line scan camera only has two-dimensional measuring capabilities, it may mistake an oil spot, shadow, or previously filled crack for an actual crack. The purpose of the LSS on the general machine is to scan the area near the potential crack location identified by the VSS to confirm or reject the presence of a crack. Furthermore, there are inherent inaccuracies in the VSS crack identification algorithm which gives it a resolution of approximately +/-1". There are also errors associated with the motion of the vehicle that will result in errors in the crack location identified by the VSS. Therefore, the LSS will also provide more precise position information to the general Robot Positioning System (RPS). Local sensing will provide range information that can accurately sense the presence and position of a crack. However, local sensing alone would not be adequate because the local sensor requires a planned path to scan for random cracks. Given the operating speed of the vehicle, the update rate and field of view of the local sensor are not adequate to track random cracks without prior knowledge of crack direction.

On the longitudinal crack sealing machine, the local sensor will provide all sensing information to the longitudinal RPS. Because the longitudinal cracks do not randomly vary in direction, it is possible to design a sensing system in which the local sensing system provides an error feedback signal to the longitudinal RPS. The start of the crack must initially be placed within the local sensor field of view, and then through real time controls and feedback provided by the local sensor, it will be possible for the longitudinal RPS to follow the longitudinal crack.

A variety of sensors technologies have been researched in order to select a sensing system which best meets the sensing requirements. The Local Sensing System which has been selected is the most cost effective, off-the-shelf component which meets all the requirements. The system selected is a laser vision sensor which measures range information using triangulation. Using triangulation, distance measurements are determined by transmitting a laser light source, then focusing the diffusely reflected light source on a photosensitive device. This method of detection has proved to be reliable and is commercially available and widely used for seam detection during automated welding.

Sensing systems based on triangulation are impervious to color variations. Therefore, a laser range finding sensor will work well on all pavements. Also, laser sensors are not sensitive to a dusty environment. Furthermore, laser triangulation is insensitive to lighting conditions because the sensor provides its own lighting via the laser. Overall, laser triangulation is a proven reliable technique for extracting three-dimensional surface characteristics.

To achieve optimal field of view and update rate from the sensor, a laser vision system using structured light was chosen. Laser vision systems based on structured light offer reliability, design simplicity, compactness, while maintaining cost effectiveness. Structured light extracts a three dimensional surface profile by projecting a laser pattern in a plane perpendicular to the surface being measures. The line of light is then observed by a CCD camera at an angle allowing the surface features to be found.

Because the goal was to use off-the-shelf components, five companies which manufacture laser vision systems were found and considered. Modular Vision Systems (MVS) was the only manufacturer who produced a commercially available sensor which met the requirements. The MVS LaserVision system provides off-the-shelf reliability and its image processing board is completely IBM compatible. It was specifically designed for tracking and inspection in robotics applications. Furthermore, this sensor is simple to use and rugged in harsh environments. The sensor has a built-in heat exchanger for cooling and a cleaning mechanism which prevents dust from settling on the lens which would distort the image. These attributes are attractive given the harsh environment associated with automated crack sealing. The MVS LaserVision system consists of the hardware and software listed in Table 2.3.1. Figure 2.3.1 contains a photo of the unit mounted in a test stand.

The sensor itself is a small package weighing 9 ounces and measuring 4" x 3" x 1.6". This package contains a laser light source, a CCD camera, and appropriate optics. The sensor will be mounted to the robot with a provided precision machined camera bracket. A vibration isolator will be placed between this bracket and the robot arm to protect the sensor from harsh vibrations and to prevent the image from being distorted. It should be noted that moderate vibration will not destroy the reliability of the camera data because the camera captures a "blur" and the image is placed optimally within this blur to compensate for the vibration. Mounting will provide flexibility of vertical and lateral adjustment for initial calibration procedures.

Power for both the laser and the camera is provided by a standard rack mounted power supply. Cabling will run between the sensor and this power supply as shown in Figure 2.3.2. Output from the camera will be input to the laser vision profile processing board, which will be placed in a standard IBM-AT compatible slot, where the camera data will be processed and the profile will be extracted. For increased performance, the profile data will be transferred to a co-processor board, which also plugs into a standard IBM-AT compatible slot.

One Laser Vision Sensor
One 30mW laser source
One sensor and laser power supply
One Laser Vision Image Processor
One co-processor board
One Microsoft compatible C5.1 library of driver routines
Menu Driven Program - Profile capture, store, segment, recall - Adjust laser intensity
Segmentation Program
IBM compatible 386-25 MHz - VGA color monitor and graphics card - Four empty full sized slots - Two serial ports - 40 MB hard drive - 4 MB RAM

Table 2.3.1 - Local Sensing System (LSS) software and hardware.

Figure 2.3.1 - Photo of local sensor mounted in test stand.

A summary of the pertinent specifications for the LSS is shown in Table 2.3.2. For detailed specifications, see the manufacturer's specifications in Appendix C.

2.3.2 - Principles of Operation

As previously discussed, a laser vision system using triangulation was chosen to locally locate a crack in pavement. Figure 2.3.3 illustrates the principle of triangulation. Distance measurements are determined by transmitting a focused laser light source onto an object and then imaging the diffusely reflected light onto a photosensitive device. The photosensitive device (PSD) is an analog light sensor that is sensitive to the intensity and position of a light spot in its field of view.

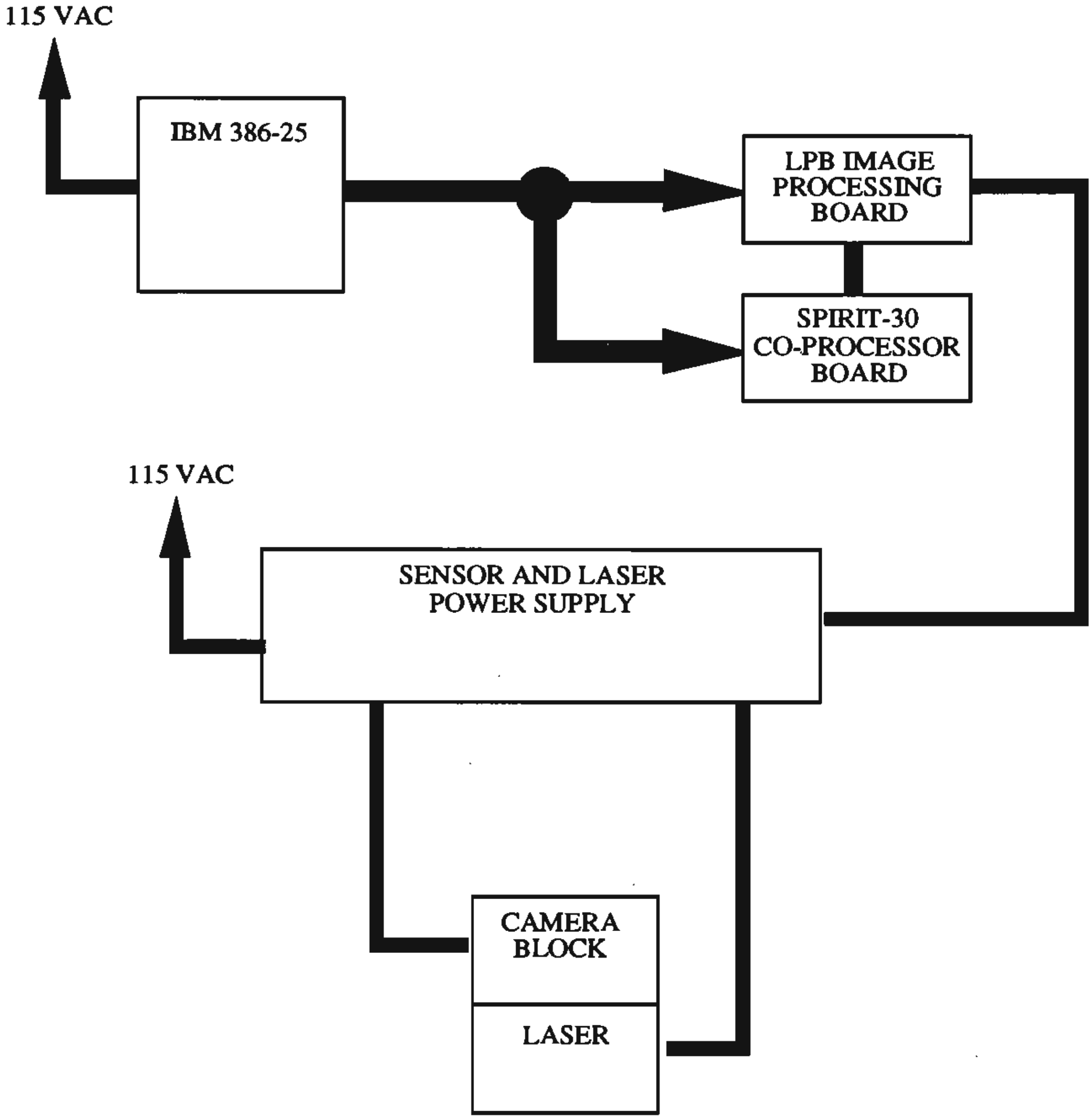


Figure 2.3.2 - LSS interconnect diagram.

Knowing the position of the image on the PSD, the distance between the detector lens and light source and the projection angle of the source, the distance measurement can be geometrically determined.

Figure 2.3.4 illustrates a laser vision system using structured light to develop three dimensional surface profiles. A laser light source is projected approximately perpendicular to the direction of	Horizontal		Vertical
Speed images/sec	60	30	
Resolution*	0.005"	0.0025"	0.006"
Accuracy position*	0.006"	0.003"	0.008"
Accuracy mismatch*			0.002"
Accuracy gap*	0.012"	0.006"	
Mounting distance to road	6.5" max.		
Field of View	4.34" max.		
Moisture	to 85%		
Vibration	typical vehicle vibration		
Temperature	-20 to 160^{o}F		
Service Life	10 years.		
Speed	60 images per second - RS170 50 images per second - CCir standard		
Water cooling	0.25 gallon per minute		
Air cooling	0.11 CFM		
Weight	9 oz (250 g)		
Processor	IBM-AT compatible, up to 8 MHz bus speed, requires 64K memory mapped space		

Table 2.3.2 - Laser vision system specifications. *Accuracy and resolution specifications are based on operating the sensor in the optimum area. The sensor will be operated outside this area to achieve a larger field of view. However, the manufacturer has guaranteed that the sensor will still meet the system requirements with a 4" field of view.

the crack. The bright line produced by this laser source on the surface is then observed by a CCD camera at an angle (20°-30°). The analog camera data is then digitized, filtered, and processed using triangulation to determine depth information.

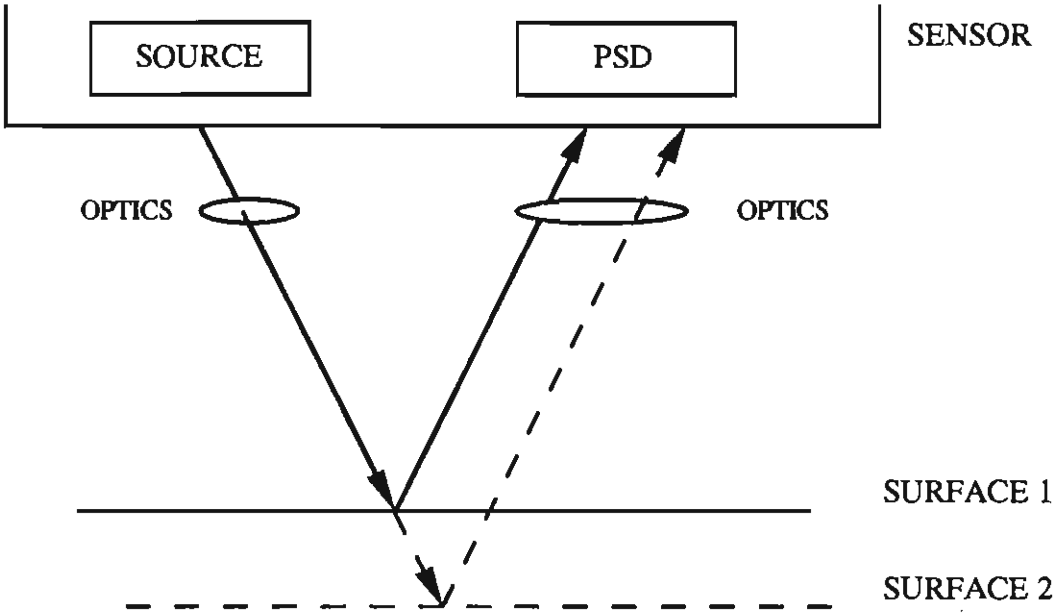


Figure 2.3.3 - Principle of triangulation.

The MVS LaserVision sensor projects a laser light source approximately perpendicular to the direction of the crack. The bright line produced by this laser source on the surface is then observed by a CCD camera at an angle (20°-30°). At this angle the line will appear to be broken.

The camera output of the laser sensor is then input to the MVS LaserVision Profile Board (LPB-200). The LPB-200 is an image processing board designed to extract the three dimensional profile from the surface of an object. The broken laser line of data acquired by the CCD camera is input to the LPB-200 and the surface profile is extracted at 60 times per second. The LPB can be used in a stand alone configuration, or with an additional co-processor board for increased performance. For the crack detecting application, a Spirit-30 co-processor board will be used. The profile data will be transferred to the co-processor board via a separate output port which is internal to the computer.

Among many features, the LPB-200 contains a histogram circuit which can operate on either an entire frame captured by the camera, or a selected window area of interest. Eight Area of Interest windows are user selectable and may be easily moved around the picture area using software routines. Performing the histogram function in hardware rather than software decreases required processor time.

The Area of Interest window can also be set to work on the extracted profile data. The profile extractor on the LPB stores x, y coordinates and light intensities of the most probable line. The data is digitally filtered in real time for accurate profile data.

The LPB board also contains an output which can control the laser intensity. This value is set in software using the provided software functions.

For more detailed feature descriptions, see the MVS LaserVision specifications in Appendix C.

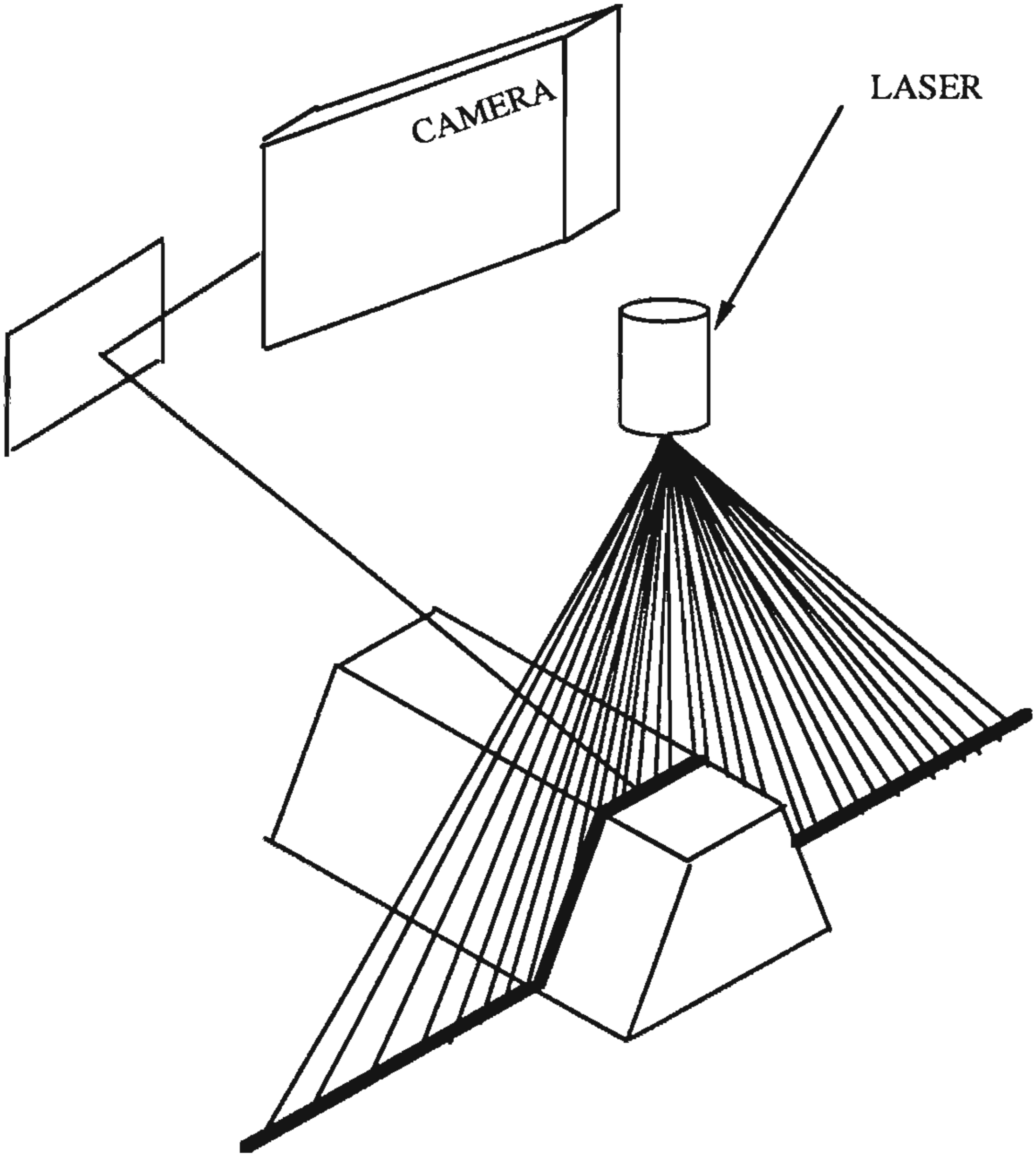


Figure 2.3.4 - Structured Light.

In order to acquire and interpret the depth information gathered by the sensor, a customized software program was developed. This program acquires data, interprets the data and extracts information relating to the position of the crack, and communicates this information to the appropriate systems.

The calling program will operate in real-time on an IBM compatible 386-25 Mhz computer. The program will be compiled using Microsoft QuickC, which is compatible with the Microsoft compiler which has compiled the functions provided with the MVS sensor. The supplied functions are contained in a library which will be linked to the calling program during compilation.

The program consists of an initialization procedure followed by the main body of the program which senses the presence of cracks in pavement. In the main body, first a profile of the road surface is captured. Next, each individual data point along the profile is analyzed to determine if a crack has been found. If a crack has been located, the program sends position information to the Robot Positioning System and then loops back to the start of the main body and captures the next profile. If the entire profile is analyzed and no crack has been located, a signal is sent to the ICU and then the program loops back the start of the main body and captures the next profile. Details of each task performed by the crack sensing program are described in the following sections.

Before the main body of the program can begin acquiring data and detecting crack location, an initialization procedure in software must be performed. During the initialization procedure, the LSS hardware is initialized. This is done through calls to initialization procedures which were provided with the MVS system software. The laser intensity is also set to maximum intensity by calling a procedure provided with the system software. Maximum intensity has reliably given optimal results on pavement surfaces during testing. Serial communication is also initialized. Two serial ports are used for communications (COM1 and COM2). The baud rate, number of stop bits, and parity (odd, even, or none) must be set for each serial port before communication can be successfully established. Using C function calls to the DOS operating system, the serial ports are initialized. Also, a profile is extracted using MVS system software and the typical roughness of the pavement surface being measured is determined. This measurement is necessary in order to determine typical depth variations from the sensor to the pavement surface. From the typical variance, an acceptable tolerance is set. Depth measurements exceeding the tolerance are therefore considered a crack. Lastly, the average depth of the pavement at the beginning of the profile is determined. This is accomplished by averaging the first twenty-five extracted data points over a typical section of pavement not containing a crack. This average is used to initialize the digital filter.

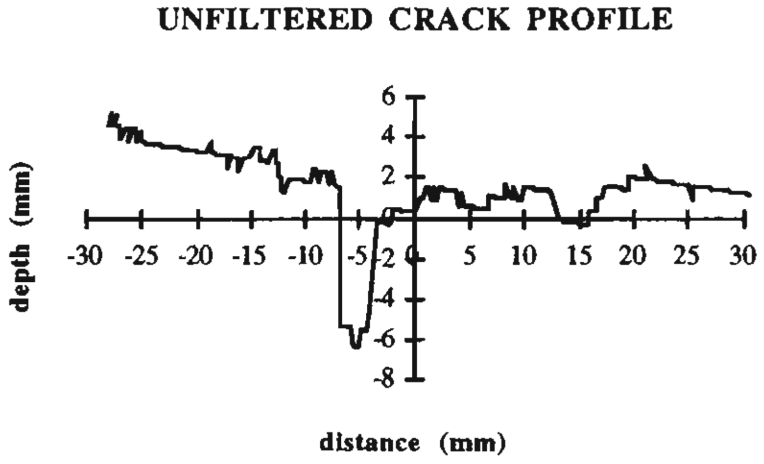
To compensate for varying surface profiles and normal height deviations in pavement, a digital low pass filter is used on the extracted data. A low pass filter was chosen to filter out normal high frequency variations in the depth measurements since the measurements of concern are low frequency components in the depth measurements - due to the presence of a crack. The digital filter was modeled after a low pass second order filter. The filter constants were determined using a Digital Fourier Transform (DFT) analysis. Figure 2.3.5 shows the profile of a crack measured by the local sensor before filtering, while Figure 2.3.6 shows the crack profile after filtering.

Before the program continues, it waits for a start signal from the ICU via the COM2 serial port. Once the signal to begin is received, the first task performed by the calling program is to determine if the sensor has located a crack. If the sensor is located over a crack, location is determined and sent to the RPS. If no crack is found, an indicating signal is sent to the ICU. This is performed by making a software function call to extract a profile and calibrate the data. The result is x, y coordinates in millimeters, where x is the direction along the line of light, and y is the depth measurement from the sensor to the surface. The zero coordinate along the x direction is located in the center of the scan. The result is stored in an array accessible to the program. Each element in this array is consecutively filtered and then compared to the previous value to determine if the starting edge of a crack has been located. If the current measurement varies by more than the accepted tolerance determined in the initialization procedure, then the program assumes that the leading edge of the crack has been located.

A simpler routine would be to compare the current data to a set point value. However, this approach was not taken because the road surface profile may vary gradually within the sensor field of view by more than the accepted tolerance without a crack being present. By comparing the current value to the previous value, gradual changes in profile are allowed for, and erroneous indications of the presence of cracks are avoided.

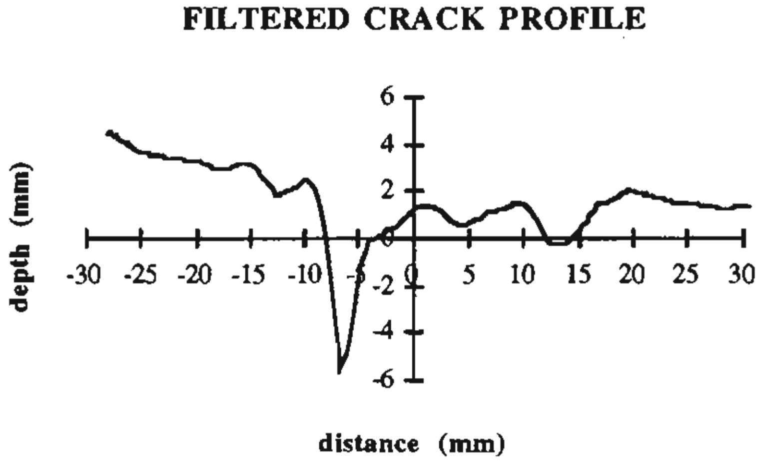
A problem arises in requiring that a previous value be set for both the filtering routine and the crack detection routine. Without an initial value, it would be impossible to detect a crack if it was located at the first data point. To solve this problem, the average value determined during the initialization routine is used.

Once the program has determined that the sensor has detected the leading edge of a crack, a flag is set, and the x coordinate of the leading edge of the crack is stored. This flag will remain set until the trailing edge of the crack is located. The trailing edge of the crack is located by again



UNFILTERED CRACK PROFILE

Figure 2.3.5 - Crack profile before filtering.



FILTERED CRACK PROFILE

Figure 2.3.6 - Crack profile after filtering.

comparing the current depth measurement to the last measurement taken. When the depth variance exceeds the tolerance, the trailing edge of the crack has been located. The x coordinate of the trailing edge of the crack is then stored.

The next software task is to determine the width of the crack. This is simply determined by subtracting the leading edge coordinate from the trailing edge coordinate. Cracks less than 1/8" in width are not sealed (same as no crack located). This effectively serves as a threshold filter which ignores unwanted spikes due to noise in the data. In the case where a crack less than 1/8" wide is located, the program continues to analyze the remainder of data points in the scan line for a crack in the same manner as described above.

Once the crack has been located and the width has been determined to be greater than 1/8", the midpoint of the crack is calculated by averaging the leading edge and trailing edge coordinates. This location constitutes the error feedback signal required by the RPS to follow the crack.

Once the error signal is determined, it is sent to the RPS directly via an RS-232 port. Using C function calls to the DOS operating system, data is sent one byte at a time per the RS-232 standard protocol.

The program then loops back to the beginning, where a profile is once again extracted and analyzed. The remainder of data points extracted during the last measurement are not further analyzed because the current machine operation does not address situations when two cracks have been located within the local sensor field of view. Because the other subsystems do not currently support the situation of multiple cracks, it would be counter productive to further analyze the data. However, only minor modifications to the program are necessary to alter the operation such that error signals can be sent to the RPS each time the sensor locates a crack, regardless of the number of cracks which have been located.

If each element of the extracted profile is analyzed and no crack location is found, an indicating signal is sent to the ICU. This signal is also sent over a second serial port (COM2). Under normal conditions, the sensor will be located over a crack and no signal will be sent to the ICU. Therefore, the ICU must constantly be polling this port to see if a signal has been sent. After the indicating signal is sent to the ICU, the program loops back to the starting point, where once again a profile is extracted and analyzed.

2.4 - Robot Positioning System (RPS)

2.4.1 - General Positioning System

2.4.1.1 Introduction

The following is a component description of the GMF-A510 SCARA manipulator and the Karel controller which have been purchased for the AHMCT crack-sealing project. The purpose of the manipulator is to guide process carts over cracks for the general crack-sealing machine. The A-510 manipulator is inverted and mounted on a linear slide on the back of the crack sealing support vehicle, as shown in Figure 2.4.1. The Karel controller is a fully integrated robot motion controller which will be responsible for all motion of the manipulator. The controller will receive input from the LSS and the ICU which will provide it with necessary information to control the manipulator, which in turn guides the process carts over cracks in the pavement.

2.4.1.2 Principles of Operation

GMF A-510 Manipulator

The GMF A-510 is a SCARA-type four degree-of-freedom manipulator. Manipulators such as this are commonly used for assembly operations, food packing and palletizing. Each joint shown is driven by a servo motor and the relative position of the joint is recorded by encoders. The servo motors and encoders are interfaced with the Karel controller. The Karel controller is able to use information from the encoders to move the end effector to locations within the workspace of manipulator. Pre-programmed information on the manipulator kinematics allows the controller to move the manipulator to points in Cartesian space with respect to the base of the manipulator. The A-510 manipulator was selected from a field of commercial manipulators on the basis of workspace, payload and controllability. The specifications for the A-510 manipulator are given in Table 2.4.1.

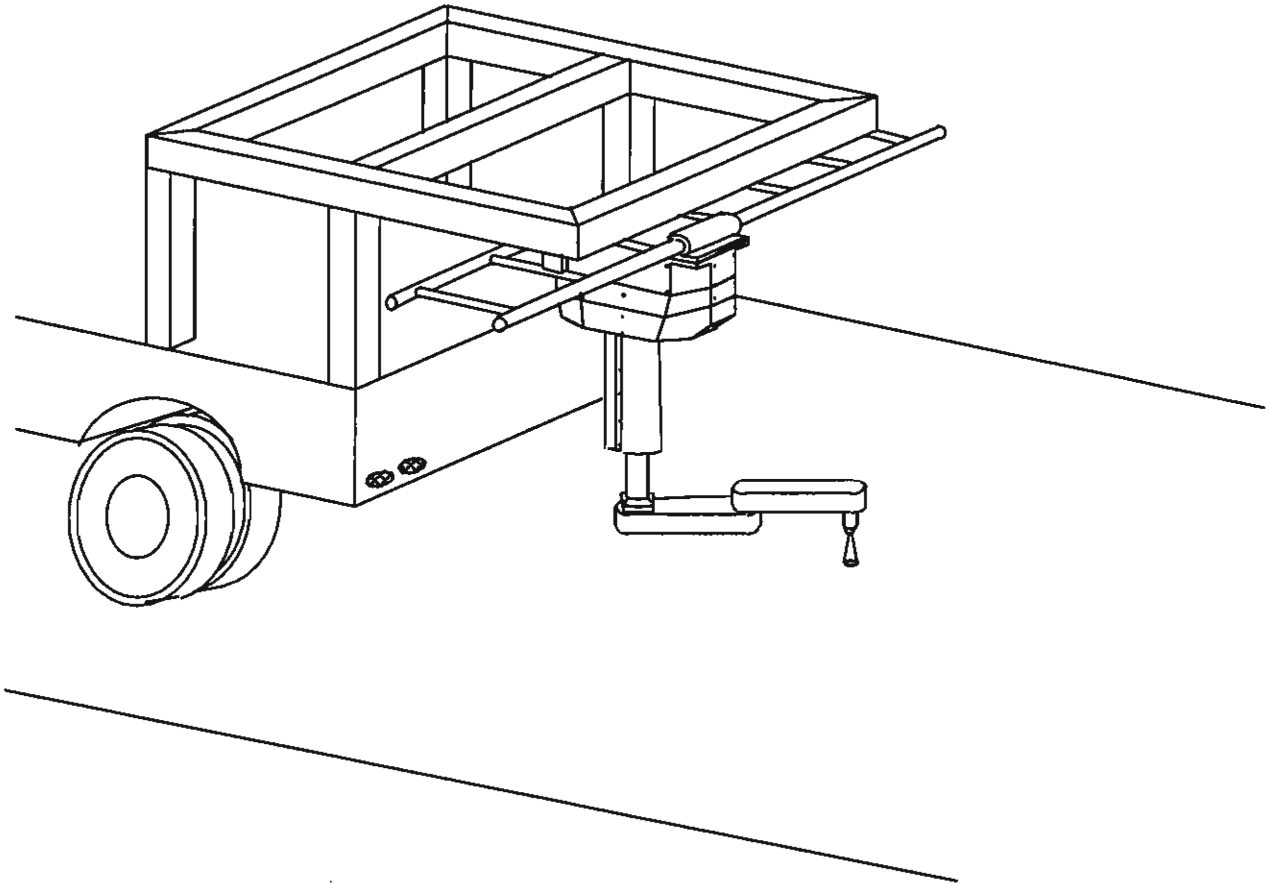


Figure 2.4.1 - The GMF A-510 mounted on a linear slide on the back of a truck.

Karel Controller

The Karel controller is capable of making calculations and running programs similar to many high level programming languages. These programs allow the robot motion to be controlled to execute a variety of complex tasks. In addition, the Karel controller can interface with other systems through digital I/O ports and serial lines. This allows the controller to operate with information from sensors and also to send motion information to other systems. The flexibility of the Karel controller and its ability to integrate with other systems make it an ideal component for use in a research environment. The important specifications for the Karel controller are listed here:

- Operator interface through Karel programming language
- Simultaneous control of up to 9 motion axes
- Capable of remote or local operation
- 2.0 MB RAM
- Serial communication capability

- Analog to Digital module
- 8 Channel Digital I/O
- 4 Channel Analog Input
- 2 Channel Analog Output
- Real time I/O monitoring
- Complete programming control structures
- Full Cartesian level transformation capability
- Continuous path motions
- Basic and advanced arithmetic functions
- Flexible operator interface

Maximum reach	29.1"
Payload	50 lb.
Weight	330 lb.
Maximum overall height	55.3"
Joint 1:	
Stroke	11.8"
Speed	27.6 in/sec
Joint 2:	
Speed	300 deg/sec
Rotation	300 degrees
Joint 3:	
Speed	300 deg/sec
Rotation	300 degrees
Joint 4:	
Speed	540 deg/sec
Rotation	540 degrees

Table 2.4.1- Specifications: GMF A-510 Manipulator.

Linear slide

The manipulator is mounted on a custom built, servo controlled linear slide which has been integrated with the Karel controller. The slide has an overall width of 8 feet to fit on the back of the crack sealing truck. The slide has 1190 mm (47 in.) of horizontal travel. The travel of the slide is restricted by such factors as the width of the manipulator base. The linear slide increases the reachable workspace of the manipulator and enhances its dexterity in certain areas near the edge of the workspace. Normally, SCARA configuration manipulators are unable to move in some directions near the outer edge of their workspace. The addition of the linear slide provides a redundant degree of freedom which allows the manipulator to move in any direction when it is near the semicircles that form the lateral boundaries of its workspace. The workspace of the manipulator with and without the linear slide is shown in Figure 2.4.2.

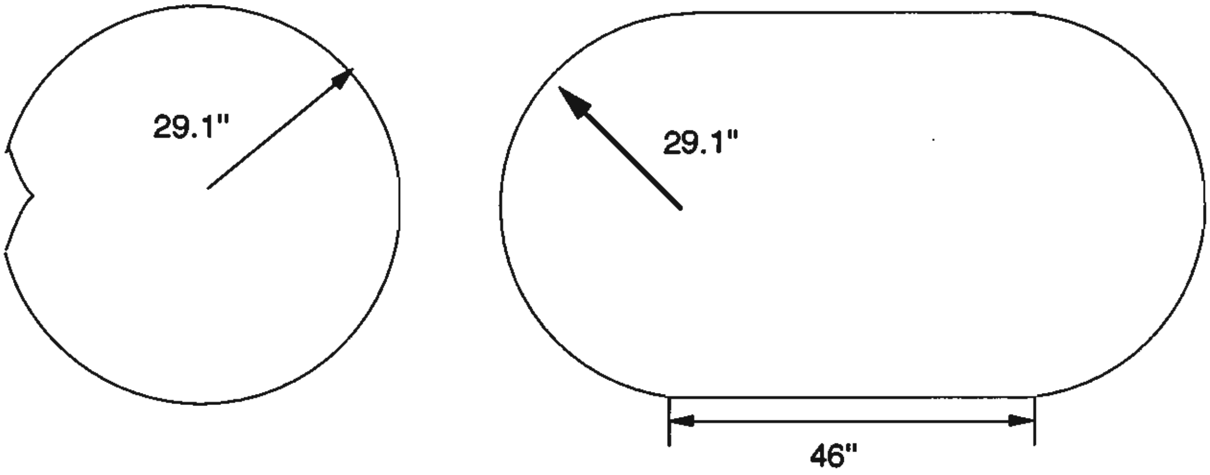


Figure 2.4.2- Workspace of the A-510 manipulator, a) without the linear slide and b) with the linear slide.

Software and Integration

The software for the Karel controller consists of an operating system, a programming language, and I/O capabilities similar to many personal computers. Applications software is written by the user in the Karel controller language. For the ACSM it was necessary to write applications software to control the motion of the manipulator, to integrate the linear slide with the manipulator, and to communicate with other subsystems including the LSS and the ICU.

The following section will describe how data from the LSS and the VSS is used to control the robot manipulator on the ACSM. A control architecture is developed that combines all available information from the VSS, the Path Planning module and the LSS. The object of the architecture is to implement crack following as quickly and efficiently as possible while making allowances for failures or errors in individual subsystems.

2.4.1.3 Feedback vs. Open-loop Control

Two types of control are available for the controller. The first type is open-loop control using the data from the VSS. Open-loop control assumes that the information from the VSS is available and correct. The data from the VSS will be processed to produce Cartesian locations in the workspace of the manipulator. The location data will consist of points along a crack as well as the crack direction at each point. Open-loop control has no way of correcting for inaccuracy in the data.

The second type of control is closed-loop or feedback control. This is the type of control that is done using the output of the LSS. Feedback data can only reveal past locations and has no a-priori knowledge of the crack. Feedback control can correct errors in the manipulator position by feeding an error signal back to the controller. The LSS is only capable of returning the offset position of the crack in its field of view with respect to the end-effector frame of the manipulator. The crack direction in feedback control can be estimated by looking at previous points along the crack.

Controlling the manipulator can involve open-loop control, feedback control or a combination of both. There will be 3 distinct modes of control based on the type of control selected. Mode 1 will use open-loop data and verify it with the LSS data. Mode 2 will use feedback data from the LSS to control both position and orientation, and Mode 3 will use feedback control to control position and open-loop control to control orientation.

Sources of Error

Two likely sources of errors for sensing cracks are the Vision Sensing System (VSS) and the Vehicle Orientation and Control System (VOC). The VSS will detect cracks in front of the support vehicle by using a line scan camera. Errors of greater than an inch are possible simply due to the pixel-resolution of the VSS algorithm. These errors are added to hardware errors such as camera resolution and vibration of the camera mount.

As the vehicle moves down the road, the VOC kinematically transforms the cracks detected by the VSS in front of the vehicle to the workspace of the robot, which is behind the vehicle. There will be more than a 40 foot separation between the front and rear of the vehicle. Sources of error for the VOC include slippage of the encoder wheels on the pavement and the resolution of the encoder wheels. Errors from the VOC will be added to the errors already introduced by the VSS.

After a crack is detected, the vehicle moves forward until the crack is in the workspace of the robot. Due to the errors described above, position errors of several inches are possible. It is also possible that no crack actually exists since the VSS can only detect gray shades and therefore may be fooled by grease stains, shadows and previously sealed cracks. The field of view of the LSS is only 3 inches, so it is highly probable that once the manipulator moves to the start of the crack, the error will be great enough that the crack will not even be in the field of view of the LSS. It is also possible that the detected crack does not even exist.

Use of Closed-loop Control

Many of the problems associated with errors from the VSS and the VOC can be eliminated by incorporating a compliant motion control algorithm with the LSS. The compliant motion algorithm uses data from the LSS to follow cracks in the pavement. However, crack following using the compliant motion algorithm with LSS limits the manipulator speed. The speed limitations are due to the fact that the algorithm must define many points to constantly control the manipulator motion. The use of a higher point density causes more joint accelerations and decelerations and hence tends to slow the effective speed of the end-effector.

Mode 1: Open-loop Control

The concept for the open-loop control architecture is to use a pre-planned path generated from VSS data, the VOC and the path planning module as much as possible. The compliant motion algorithm will be used to search for the crack if the errors in the pre-planned path become larger than the field of view of the LSS. Once the crack is located by the compliant motion algorithm, the actual crack location can be sent back to the ICU. The offset in the crack location can then be used to help correct errors in the pre-planned path through the path planning module.

Mode 2: Feedback Control for Position and Orientation

The compliant motion algorithm can also completely override use of a pre-planned path in the event of a system failure of the VSS, the VOC, or the ICU. In this case, the end-effector can be moved to the beginning of the crack and aligned with the starting direction of travel using the teach pendant. The compliant motion algorithm will then be executed for the crack following operation. The end-effector speed using the compliant motion algorithm will be slower than if pre-planned path data were available.

Mode 3: Feedback Control for Position and Open-loop Control for Orientation

A scheme that uses the LSS data to control the position of the end-effector and VSS data to control the orientation of the end-effector can also be used. This algorithm will work well if there are errors in the location of the crack from the VSS, but its shape is generally known. The direction of the crack will be sent to the RPS according to its location along the 'x' axis of the world coordinate system. The control algorithm will use the LSS to follow the crack, but the direction information from the VSS will control the orientation of the end-effector. This scheme will require the approximate Cartesian location of the start of the crack. from the VSS

Error Handling

An error handling routine will be called any time the crack is lost from the field of view of the local sensor. The same error handling routine will be used regardless of whether the motion is being controlled by data from the VSS or the LSS. The search algorithm will scan at right angles for the crack according to the most recent crack direction. The searching algorithm is essentially the same as the compliant motion algorithm except that the tangential velocity is set to zero. If the crack is still not found, a search will be conducted in the opposite direction as well. Limits are set on the distance to be searched. If the crack is not found within the specified limits, an error signal is sent to the ICU. On receipt of such an error signal, the ICU can then indicate the need for manual placement of the manipulator on the crack.

Control Architecture

The control architecture will be defined by the following algorithm:

(1) The location of a crack will be determined by the VSS, VOC etc. and a path consisting of Cartesian points within the workspace of the robot will be calculated and sent to the RPS.

(2) The manipulator will move to the beginning of the crack using the path generated by the ICU and path planning.

(3) The local sensor will be checked to determine if a crack is present. If no crack is found, the RPS will signal the ICU and begin searching for the crack at right angles using the LSS. The result of the search--either 'no crack found' or the location of the crack will be sent to the ICU. The RPS will then wait for an updated path to be sent from the ICU and will resume motion with step (2).

(4) Once the location of the crack has been verified by the LSS and the path has been updated, if necessary, the manipulator will follow the crack and the LSS output will be monitored. The LSS data can be used to determine if the manipulator runs off of

the crack. If this occurs, the ICU will be signaled, and a search for the crack will begin as in step (3). Once again, the result of the search will be sent to the ICU and the RPS will wait for an updated path before resuming motion as in step (2).

(5) When the manipulator reaches the last point defined on the path it will signal the ICU to indicate that the end of the crack has been reached.

Additional options:

(a) It will be possible to define a maximum offset within the field of view of the sensor. If the offset from the center of the end-effector to the crack exceeds the maximum offset, the manipulator will center itself on the crack using the LSS and signal the ICU in a similar manner to the signaling for the search routine described above.

(b) It will be possible to override all data from the ICU and follow cracks using only the RPS and the LSS. This override will require the manipulator to be moved to the start of the crack and aligned in the direction of travel using the teach pendant. The motion speed for this override will be much slower than if global data were used.

(c) Crack following can also be conducted using crack direction data from the VSS and using closed-loop control with the LSS for position control.

Communications

Communication to and from the RPS will be accomplished by means of serial lines. Two separate lines will be used, one for communication with the LSS and one for communications with the ICU.

2.4.2 - Longitudinal Robotic Positioning System

2.4.2.1 - Component Description

The longitudinal robotic positioning system (LRPS) is the system that supports local sensor, the router, the vacuum and heater/blower ducts and the sealant applicator unit during operations on longitudinal pavement cracks running parallel to the roadway. Design and development of the LRPS was defined by two basic subsystems, the mechanical frame known as the longitudinal machine and the actuator and control components. Initial development and testing during Phase II emphasized the design and fabrication of the longitudinal machine, which includes the cart that carries the applicator and peripheral system (APS) components, a linear slide table, and the connecting linkages. Selection and purchase of a commercially available actuator and control system occurred simultaneously during Phase II and delivery and integration occurred in Phase III. Figure 2.4.3 shows a photo of the LRPS with the APS components installed in the final configuration.

Figure 2.4.3 - LRPS with APS components.

Longitudinal Machine

The first of two longitudinal machines was fabricated during Phase II to serve as the test vehicle for the APS components and a prototype to the final longitudinal machine. During Phase III Caltrans began sealant applicator testing with the first machine. Drawings were updated with design changes and used to fabricate the second machine which was installed on the truck in the final configuration. Important design criteria that were defined and incorporated during development were as follows:

1) The actuator control system had to be simple and the linear motion was limited to a single degree of freedom. Actuator motion was to be transferred directly to the cart through the linkage.
2) The linkage was designed to minimize lateral translation of the cart due to the changes in elevation and angle of the road surface since this would have to be compensated for by the actuator.
3) Stowage was to be simple.

4) A cart length of 5 feet was required to allow installation of all the APS components in the worst case configuration. Lateral movement of the cart was limited to 12 inches total, representative of driver's abilities when crack sealing.

5) Simplification of the design was important to prove the concept and have a working prototype to support testing. Development for commercialization would address issues such as optimum cart size and stowage design.

6) Configuration of the LRPS was to allow for installation on truck beds of various heights with minor modifications.

Figure 2.4.4 depicts the basic components of the longitudinal machine which are described in the following paragraphs. It should be noted that the item numbers discussed correspond with those of the figure *and* those of the detail assembly drawing, SHRP(LPS)LM-A100 in Appendix D.2.2.

1) Linear slide table (item 2) - The base of the table (item 1) is bolted to the truck bed and can be adjusted by shimming to set the slide table parallel to the road,. A linear actuator (item 11) with a 12 inch stroke drives the slide table which is mounted on two linear bearings (item 12), 39 inches in length.

2) Upper link (item 3) - During operation of the machine, this link serves as a structural member rigidly attached to the slide table and extending down to the lower link attached to the cart. The linear movement of the table on top of the truck is transferred by this link down to the cart (item 5) near the road. It is hinged to the table at one end and can be unlocked to allow it to rotate upward lifting the cart up for stowage. The length of the link between the attachment point on the table to the lower link would be sized for the vehicle to which it is attached, and this is the only part that would need to be modified in mounting the unit to another vehicle.

3) Lower link (item 4) - The link is hinged at the upper link and the center of the cart. The hinge points allow the cart to translate vertically and rotate about its longitudinal axis as it follows the road. Lateral translation of the linear table is transferred to the cart across this link. At nominal dimensions on a flat road the axes of both hinge points line in a plane parallel to the road. The bend in the arms of the link provide clearance to allow the casters (item 10) on the cart to rotate 360°.

4) Cart (item 5) - The cart is a simple rectangular frame usually mounted on a pair of casters. The casters support the weight of the frame and components while maintaining a constant height with respect to the road surface (see Figure 2.4.5). When operated in a configuration that includes the router (see Figure 2.4.6), the casters are removed and the cart is attached to the frame of the router. Rotation of the cart about the transverse axis (pitch) is prevented by the reaction forces across the

lower link. So, the cart longitudinal axis is always parallel to the longitudinal axis of the truck. Bolt holes are placed in the frame as required to attach the APS components.

During operation the links allow the cart to follow the road surface defined by the contact points at the casters. The cart is free to move vertically and rotate about the hinges on the lower link as shown in Figure 2.4.7. The stowage of the cart is achieved by rotating the upper link upward as shown. This is presently done by using an overhead hoist attached to the lower link. Modifications to the upper link and the use of hydraulic actuators during commercialization would allow for other stowing configurations.

Actuator and Controller

A commercially available prepackaged electro-hydraulic linear drive system, Parker Electrohydraulics PMC 10 Digital Process Servo Valve Controller and Actuator, was selected for the longitudinal RPS. The system uses a programmable digital controller to operate a servo valve on a hydraulic cylinder and operates in a closed loop with the feedback from a position transducer on the hydraulic cylinder. The controller can be programmed to accept input from the local sensing system (LSS) across an RS-232 port. Given a value for position, the controller will then drive the actuator to the location at preprogrammed acceleration and velocity values. Information will be provided by the LSS and the controller operating at 10 Hz. The chosen system has higher speed capabilities with minor hardware and software modifications, although the noted rate is expected to be more than adequate.

2.4.2.2 - Principles Of Operation

The longitudinal RPS is the subsystem that places the APS components over longitudinal pavement cracks running parallel to the roadway. The system consists of a cart in which these APS components can be installed in various configurations and, an actuation and control system that guides it.

The cart is attached to the side of the road maintenance vehicle with a mechanical linkage that allows the cart to move laterally a distance representative of crack geometry and driver capabilities as the vehicle is driven alongside the crack. The lateral movement is controlled automatically to correct for the relative position of the vehicle to the crack. The linkage also allows the cart to be retracted from the road when not in operation.

A single actuator provides the force to move the cart. It is driven by a controller that receives input from the LSS which is mounted at the centerline, forward end of the cart. As the cart is pulled forward, its lateral location is continually updated to keep the cart centerline over the crack, as measured at the local sensor.

The APS components, which are located on the centerline of the cart, prepare and fill the crack as it passes beneath them. These components are modular and can be installed in various configurations to allow for different crack sealing methods used by various DOTs. The support equipment necessary to operate the various components is located on the vehicle.

The configuration of the components installed in the cart imposes design constraints that specify the overall size of the cart, structural strength, stowing configuration options, and the limits on the system's ability to follow changes in crack path. To maintain flexibility in the development of the system and APS components, a worst case configuration was considered. This includes installation of the components in the following order beginning at the forward end of the cart (see Figure 2.4.6):

1) Local Sensor - Required for all configurations to provide for crack location through the LSS.
2) Vacuum Duct - Required for use in combination with the router to remove debris from the area around the crack and control exposure to dust created during routing. This ducting would be integrated within the body of the router.
3) Router - Required for some methods of crack preparation prior to sealing.
4) Heater/Blower Duct - Required for some methods of crack preparation. It could conceivably be used in conjunction with the router for preparation of the crack. With this configuration, a pyrometer used to sense the road surface temperature is located immediately behind the hot air duct to control the application of heat.
5) Sealant applicator - Required for sealing the crack. It places a five inch wide band over the prepared crack and will always be the last component on the cart.

When following a crack, the combination of all five components is most limiting since they are located on the centerline of the cart and define the minimum distance between the local sensor and sealant applicator. This distance then imposes a limit on the maximum rate of change in relative position between the crack and the maintenance vehicle (see Figure 2.4.8). Actuation of the cart is limited to translation in the direction perpendicular to the centerline of the cart, which is parallel to the direction of travel of the vehicle. The cart follows the crack located by the sensor at the forward end, which has a maximum four inch field of view. The applicator at the aft end lays a band of sealant five inches wide. The router cannot cut a path without a significant forward component since the cart does not have a rotational component which would allow the router to follow a circular path. These basic limitations on the crack following capability are inherent in the definition of 'parallel crack' but, as noted, are dependent on factors that include selection of crack preparation components.

The LRPS will operate as a component of the crack sealing machine controlled through the ICU, but it can be used independently as a self-contained unit with the LSS output provided directly to the controller. In addition testing of the sealant applicator alone using the first longitudinal machine has demonstrated successful operation with lateral positioning by the driver. The capability to operate as a self-contained system, the relative simplicity of its operation, and the modularity of the APS components, support the commercial viability of the LRPS.

Figure 2.4.4 - Longitudinal machine basic components. Item numbers correspond to assembly drawing SHRP(LPS)LM-A100 in Appendix D.2.2.

Figure 2.4.5 - **Longitudinal configuration without router attached. Note the pneumatic casters which support the linkage.**

Figure 2.4.6 - Longitudinal configuration with router attached. Note: the casters have been removed, the linkage is supported by the router wheels.

Points

A - The point, located on the road surface, that is being tracked. Refer to Figure 2.6.3.

$B_{[\#]}$ - The point (on the truck), located on the center line of the right and left encoders, at a distance "W" to the left of the right encoder. The subscript identifies the variable to which it is attached as belonging to the [#] step. Refer to Figure 2.6.3.

Miscellaneous Variables

$A_{[\#]}$ - The distance between a point "A" and the point "$B_{[\#]}$". Refer to Section 2.6.4.2.1 and Figure 2.6.7.

$Ax_{[\#]\,\#}$ - The "x" distance, measured with respect to a particular reference frame (denoted by the subscript "#"), between a point "A" and the origin of the [#] reference frame. The subscript [#] denotes the step of the truck to which this value belongs. Refer to Section 2.6.4.2.1 and Figure 2.6.6.

$Ay_{[\#]\,\#}$ - The "y" distance, measured with respect to a particular reference frame (denoted by the subscript "#"), between a point "A" and the origin of the [#] reference frame. The subscript [#] denotes the step of the truck to which this value belongs. Refer to Section 2.6.4.2.1 and Figure 2.6.6.

$ARCl_{[\#/\#]}$ - The length of the arc traversed by the left encoder from step "[#/" to step "/#]". Refer to Section 2.6.4.2.1 and Figure 2.6.3.

$ARCr_{[\#/\#]}$ - The length of the arc traversed by the right encoder from step "[#/" to step "/#]". Refer to Section 2.6.4.2.1 and Figure 2.6.3.

$B_{[\#/\#]}$ - The distance between one point "B" (denoted by the subscript "[#/") and another point B (denoted by the subscript "/#]. Refer to Section 2.6.4.2.1 and Figure 2.6.7.

$Bx_{[\#/\#]\,\#}$ - The "x" distance, measured with respect to a particular reference frame (denoted by the subscript "#"), between one point "B" (denoted by the subscript "[#/") and another point B (denoted by the subscript "/#]. Refer to Section 2.6.4.2.1 and Figure 2.6.5.

$Bx(cum)_0$ - The cumulative sum of all "$Bx_{[\#/\#]\,0}$" values up to and including the value for the last step of the truck. This variable makes sense only when referring to the "$_0$" reference frame.

$By_{[\#/\#]\,\#}$ - The "y" distance, measured with respect to a particular reference frame (denoted by the subscript "#"), between one point "B" (denoted by the subscript "[#/") and another point B (denoted by the subscript "/#]. Refer to Section 2.6.4.2.1 and Figure 2.6.5.

$By(cum)_0$ - The cumulative sum of all "$By_{[\#/\#]0}$" values up to and including the value for the last step of the truck. This variable makes sense only when referring to the "$_0$" reference frame.

n - The variable "n" refers to either the current step of the truck or the current moving coordinate frame depending on the context in which it is used. Additionally, "n-1" refers to the previous step or moving coordinate frame, "n-2" refers to the step or moving coordinate frame previous to the "n-1" step or moving coordinate frame, etc.

$Nl_{[\#/\#]}$ - The number of encoder pulses counted by the left encoder from step "[#/" to step "/#]".

$Nr_{[\#/\#]}$ - The number of encoder pulses counted by the right encoder from step "[#/" to step "/#]".

$Rb_{[\#/\#]}$ - The length of the radius between step "[#/," and step "/#]" of the truck drawn from the center of rotation of the truck and the arc traced by the point "B" (on the truck). Refer to Section 2.6.4.2.1 and Figure 2.6.3.

$Rl_{[\#/\#]}$ - The length of the radius between step "[#/," and step "/#]" of the truck drawn from the center of rotation of the truck and the arc traced by the left encoder wheel. Refer to Section 2.6.4.2.1 and Figure 2.6.3.

$Rr_{[\#/\#]}$ - The length of the radius between step "[#/," and step "/#]" of the truck drawn from the center of rotation of the truck and the arc traced by the right encoder wheel. Refer to Section 2.6.4.2.1 and Figure 2.6.3.

2.6.4.3 - The Kinematics of the Problem

General Kinematics

First equations for several of the basic variables are derived. From Figure 2.6.3, it can be easily shown that:

$$ARCl_{[n-1/n]} = 2 \times \pi \times Re \left(\frac{Nl_{[n-1/n]}}{Ne_{[n-1/n]}} \right) \qquad (2.6.1)$$

and

$$ARCr_{[n-1/n]} = 2 \text{ x } \pi \text{ x } Re \left(\frac{Nr_{[n-1/n]}}{Ne_{[n-1/n]}}\right). \tag{2.6.2}$$

Next, a formula for $Rr_{[n-1/n]}$ is derived. From Figure 2.6.3, it can be seen that:

$$\frac{ARCr_{[n-1/n]}}{Rr_{[n-1/n]}} = \frac{ARCl_{[n-1/n]}}{Rl_{[n-1/n]}} \tag{2.6.3}$$

and

$$Rl_{[n-1/n]} = Rr_{[n-1/n]} + D. \tag{2.6.4}$$

Substituting Eqns. 2.6.4 into 2.6.3 and rearranging,

$$Rr_{[n-1/n]} = \left(\frac{(ARCr_{[n-1/n]})\ D}{ARCl_{[n-1/n]} - ARCr_{[n-1/n]}}\right). \tag{2.6.5}$$

Also, from Figure 2.6.3,

$$Rb_{[n-1/n]} = Rr_{[n-1/n]} + W, \tag{2.6.6}$$

$$\theta_{[n]} = \left(\frac{ARCr_{[n-1/n]}}{Rr_{[n-1/n]}}\right), \tag{2.6.7}$$

and

$$\theta_{[n]} = \left(\frac{ARCl_{[n-1/n]} - ARCr_{[n-1/n]}}{D}\right). \tag{2.6.8}$$

From Figure 2.6.4,

$$\phi_{[n]} = \tan^{-1}\left(\frac{Ay_{[n-1]\,n-1} - By_{[n-1/n]\,n-1}}{Ax_{[n-1]\,n-1} - Bx_{[n-1/n]\,n-1}}\right) \tag{2.6.9}$$

Figure 2.6.3 - VOC system kinematics.

Figure 2.6.4 - VOC system kinematics.

Kinematics with respect to Local Reference Frame

Now, from Figure 2.6.5 it can be seen that:

$$\Delta Bx_{[n-1/n]\ n-1} = Rb_{[n-1/n]} \sin(\theta_{[n]}) \qquad (2.6.10)$$

and

$$\Delta By_{[n-1/n]\ n-1} = Rb_{[n-1/n]} (1 - \cos(\theta_{[n]})). \qquad (2.6.11)$$

Now substitute Eqn. 2.6.5 into Eqn. 2.6.6. Then substitute Eqns. 2.6.6 and 2.6.8 into Eqns. 2.6.10 and 2.6.11,

$$\Delta Bx_{[n-1/n]\ n-1} = \left(\frac{(ARCr_{[n-1/n]})\ D}{ARCl_{[n-1/n]} - ARCr_{[n-1/n]}} + W\right) \sin\left(\frac{ARCl_{[n-1/n]} - ARCr_{[n-1/n]}}{D}\right) \qquad (2.6.12)$$

refer to Figure 2.6.5

and

$$\Delta By_{[n-1/n]\ n-1} = \left(\frac{(ARCr_{[n-1/n]})\ D}{ARCl_{[n-1/n]} - ARCr_{[n-1/n]}} + W\right)\left(1 - \cos\left(\frac{ARCl_{[n-1/n]} - ARCr_{[n-1/n]}}{D}\right)\right). \qquad (2.6.13)$$

refer to Figure 2.6.5

Now develop equations for point A. Referring to Figure 2.6.6,

$$Ax_{[n]\ n} = \left(\sqrt{(Ax_{[n-1]\ n-1} - \Delta Bx_{[n-1/n]\ n-1})^2 + (Ay_{[n-1]\ n-1} - \Delta By_{[n-1/n]\ n-1})^2}\right) \cos(\phi_{[n]} + \theta_{[n]}) \qquad (2.6.14)$$

and

$$Ay_{[n]\ n} = \left(\sqrt{(Ax_{[n-1]\ n-1} - \Delta Bx_{[n-1/n]\ n-1})^2 + (Ay_{[n-1]\ n-1} - \Delta By_{[n-1/n]\ n-1})^2}\right) \sin(\phi_{[n]} + \theta_{[n]}). \qquad (2.6.15)$$

Substituting Eqns. 2.6.8 and 2.6.9 into Eqns. 2.6.14 and 2.6.15,

$$Ax_{[n]\ n} = \left(\sqrt{(Ax_{[n-1]\ n-1} - \Delta Bx_{[n-1/n]\ n-1})^2 + (Ay_{[n-1]\ n-1} - \Delta By_{[n-1/n]\ n-1})^2}\right)\ x \qquad (2.6.16)$$

$$\cos\left(\tan^{-1}\left(\frac{Ay_{[n-1]\ n-1} - \Delta By_{[n-1/n]\ n-1}}{Ax_{[n-1]\ n-1} - \Delta Bx_{[n-1/n]\ n-1}}\right) + \left(\frac{ARCl_{[n-1/n]} - ARCr_{[n-1/n]}}{D}\right)\right)$$

refer to Figure 2.6.6

and

$$Ay_{[n]\,n} = \left(\sqrt{(Ax_{[n-1]\,n-1} - \Delta Bx_{[n-1/n]\,n-1})^2 + (Ay_{[n-1]\,n-1} - \Delta By_{[n-1/n]\,n-1})^2}\right) \times \qquad (2.6.17)$$

$$\sin\left(\tan^{-1}\left(\frac{Ay_{[n-1]\,n-1} - \Delta By_{[n-1/n]\,n-1}}{Ax_{[n-1]\,n-1} - \Delta Bx_{[n-1/n]\,n-1}}\right) + \left(\frac{ARCl_{[n-1/n]} - ARCr_{[n-1/n]}}{D}\right)\right).$$

refer to Figure 2.6.6

Kinematics w/Respect to Global Reference Frame

Referring to Figure 2.6.4, it can be seen that:

$$\psi_{[n-1/n]} = \tan^{-1}\left(\frac{-\Delta By_{[n-1/n]\,n-1}}{\Delta Bx_{[n-1/n]\,n-1}}\right) \qquad (2.6.18)$$

and

$$\theta Total = \theta_{[1]\,0} + \ldots + \theta_{[n-1]\,n-2} + \theta_{[n]\,n-1}. \qquad (2.6.19)$$

From Figure 2.6.7:

$$B_{[n-1/n]} = \sqrt{(\Delta Bx_{[n-1/n]\,n-1})^2 + (\Delta By_{[n-1/n]\,n-1})^2}. \qquad (2.6.20)$$

Now, referring to Figure 2.6.5,

$$\Delta Bx_{[n-1/n]\,0} = B_{[n-1/n]} \cos(\psi_{[n]\,n-1} + \theta Total + \theta_{[n]\,n-1}) \qquad (2.6.21)$$

and

$$\Delta By_{[n-1/n]\,0} = B_{[n-1/n]} \sin(\psi_{[n]\,n-1} + \theta Total + \theta_{[n]\,n-1}). \qquad (2.6.22)$$

Note that the correct signs (+/-) of $\Delta Bx_{[n-1/n]\,0}$ and $\Delta By_{[n-1/n]\,0}$ in Eqns. 2.6.21 and 2.6.22 may not be preserved since $B_{[n-1/n]}$ (which was calculated in Eqn. 2.6.20) was calculated by squaring $\Delta Bx_{[n-1/n]\,n-1}$ and $\Delta By_{[n-1/n]\,n-1}$, adding them, and taking their square root. This must be taken into account in the computer program.

Figure 2.6.5 - VOC system kinematics.

Figure 2.6.6 - VOC system kinematics.

Substituting Eqns. 2.6.8, 2.6.18, 2.6.19, and 2.6.20 into Eqn. 2.6.21,

$$\Delta Bx_{[n-1/n]\,0} = \left(\sqrt{(\Delta Bx_{[n-1/n]\,n-1})^2 + (\Delta By_{[n-1/n]\,n-1})^2}\right) \;\mathrm{x} \tag{2.6.23}$$

$$\cos\left(\tan^{-1}\left(\frac{-\,\Delta By_{[n-1/n]\,n-1}}{\Delta Bx_{[n-1/n]\,n-1}}\right) + \left(\frac{ARCl_{[1/2]} - ARCr_{[1/2]}}{D}\right) + \ldots + \underset{\boxed{\text{refer to Figure 2.6.5}}}{\left(\frac{ARCl_{[n-2/n-1]} - ARCr_{[n-2/n-1]}}{D}\right)}\right).$$

Similarly, substituting Eqns. 2.6.8, 2.6.18, 2.6.19, and 2.6.20 into Eqn. 2.6.22,

$$\Delta By_{[n-1/n]\,0} = \left(\sqrt{(\Delta Bx_{[n-1/n]\,n-1})^2 + (\Delta By_{[n-1/n]\,n-1})^2}\right) \;\mathrm{x} \tag{2.6.24}$$

$$\sin\left(\tan^{-1}\left(\frac{-\,\Delta By_{[n-1/n]\,n-1}}{\Delta Bx_{[n-1/n]\,n-1}}\right) + \left(\frac{ARCl_{[1/2]} - ARCr_{[1/2]}}{D}\right) + \ldots + \underset{\boxed{\text{refer to Figure 2.6.5}}}{\left(\frac{ARCl_{[n-2/n-1]} - ARCr_{[n-2/n-1]}}{D}\right)}\right).$$

Now we develop equations for point "A". First,

$$\Delta Bx(cum)_0 = \Delta Bx_{[1/2]\,0} + \ldots + \Delta Bx_{[n-2/n-1]\,0} + \Delta Bx_{[n-1/n]\,0} \tag{2.6.25}$$

and

$$\Delta By(cum)_0 = \Delta By_{[1/2]\,0} + \ldots + \Delta By_{[n-2/n-1]\,0} + \Delta By_{[n-1/n]\,0}. \tag{2.6.26}$$

From Figure 2.6.4, it is seen that:

$$\beta_{[n]\,0} = \left(\frac{Ay_{[1]\,0} - \Delta By(cum)_0}{Ax_{[1]\,0} - \Delta Bx(cum)_0}\right). \tag{2.6.27}$$

Now, referring to Figure 2.6.6:

$$Ax_{[n]0} = \left(\sqrt{(Ax_{[1]0} - \Delta Bx(cum)_0)^2 + (Ay_{[1]0} - \Delta By(cum)_0)^2}\right) \cos(\beta_{[n]0}) \qquad (2.6.28)$$

and

$$Ay_{[n]0} = \left(\sqrt{(Ax_{[1]0} - \Delta Bx(cum)_0)^2 + (Ay_{[1]0} - \Delta By(cum)_0)^2}\right) \sin(\beta_{[n]0}). \qquad (2.6.29)$$

Substituting Eqn. 2.6.27 into Eqns. 2.6.28 and 2.6.29,

$$Ax_{[n]0} = \left(\sqrt{(Ax_{[1]0} - \Delta Bx(cum)_0)^2 + (Ay_{[1]0} - \Delta By(cum)_0)^2}\right) \times \qquad (2.6.30)$$

$$\cos\left(\frac{Ay_{[1]0} - \Delta By(cum)_0}{Ax_{[1]0} - \Delta Bx(cum)_0}\right).$$

refer to Figure 2.6.6

Similarly,

$$Ay_{[n]0} = \left(\sqrt{(Ax_{[1]0} - \Delta Bx(cum)_0)^2 + (Ay_{[1]0} - \Delta By(cum)_0)^2}\right) \times \qquad (2.6.31)$$

$$\sin\left(\frac{Ay_{[1]0} - \Delta By(cum)_0}{Ax_{[1]0} - \Delta Bx(cum)_0}\right).$$

refer to Figure 2.6.6

2.6.5 - VOC Computer Program and System Interface

The VOC system consists of two optical encoders, a computer interface card, and software. The encoders output a square wave pulse as the vehicle moves, and the computer interface card records the number of pulses.

The software performs three functions: 1) read the number of recorded pulses on the computer interface card, 2) calculate the vehicle's new position and heading based on the number of recorded pulses, and 3) provides the RPS crack locations upon request. The new position and heading are calculated in the program using kinematics schemes similar to those previously described. When the RPS requests new crack locations, the program executes a matrix transformation routine that provides an updated crack location based on the current vehicle location and the old crack locations provided by the VSS.

Figure 2.6.7 - VOC system kinematics.

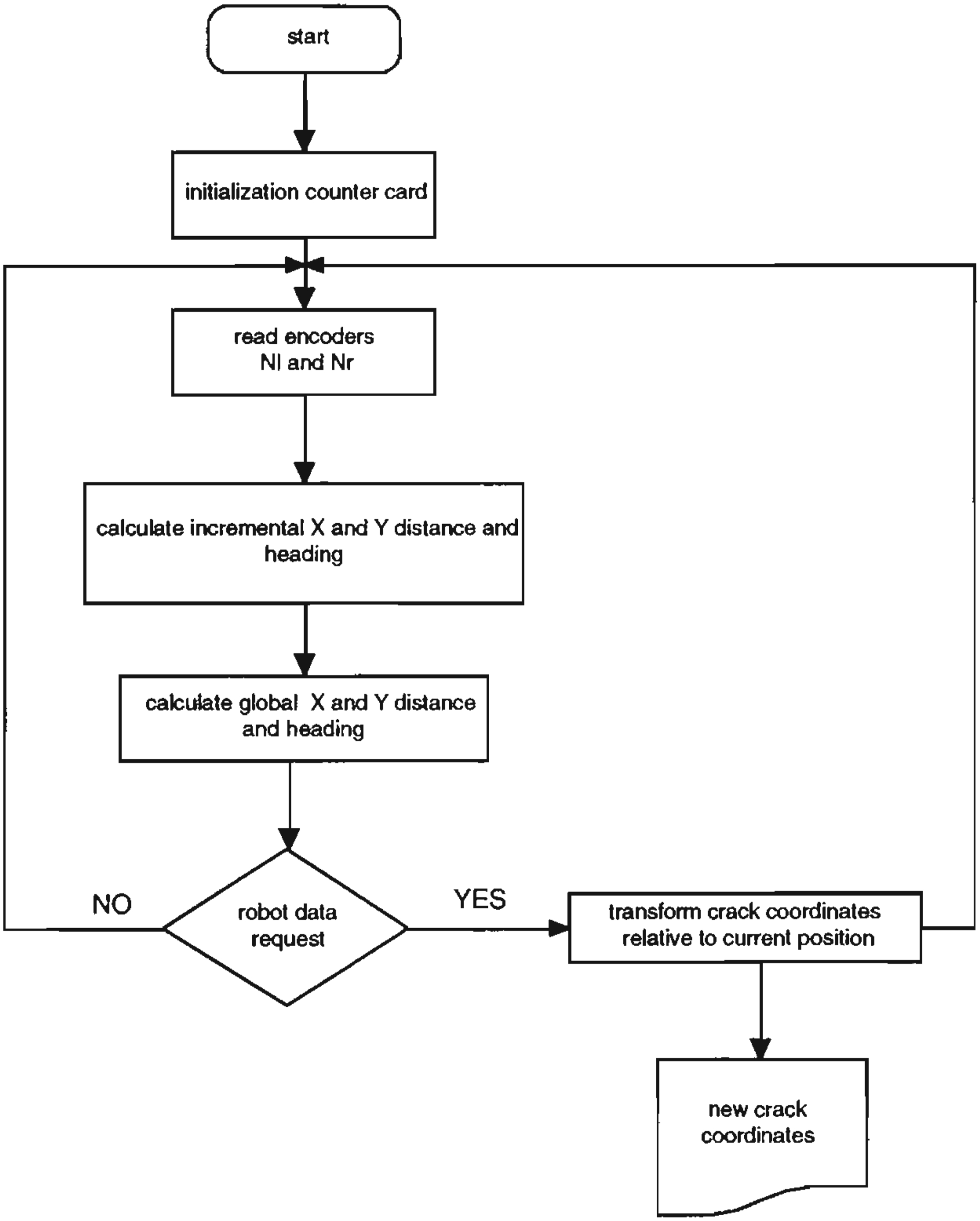


Figure 2.6.8 - Flow chart of VOC system and interface.

2.6.6 - Cart Test of Integrated First Generation Prototype

The integrated first generation prototype of the VOC system was recently tested and debugged on a specially designed test cart (see Figure 2.6.9). The test cart was used as the VOC system platform for the first generation prototype in place of the crack sealing truck. The test cart provided a convenient, scaled-down test platform on which the VOC system could be easily tested and debugged. In Phase III, the second generation prototype will be developed and manufactured as well as integrated with the ACSM. It will be essentially identical to the first generation prototype except for refinements in the design and modifications of the fifth wheels what will allow the second generation prototype to be mounted directly to the crack sealing truck.

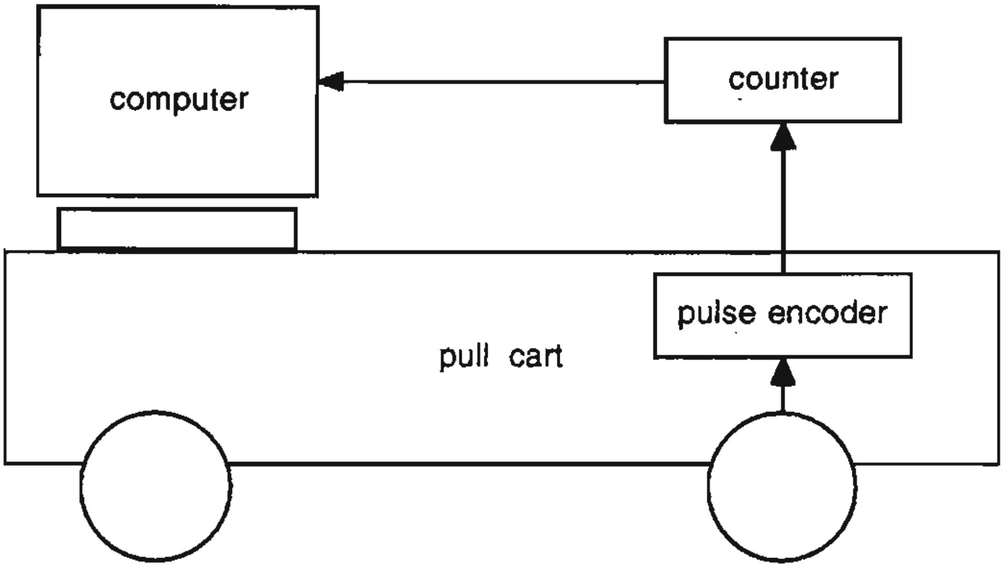


Figure 2.6.9 - Schematic illustration of test cart and integrated first generation VOC system prototype.

2.6.7 - Cart Test of Integrated Second Generation Prototype

The test cart will be used in place of the crack sealing truck for initial testing and troubleshooting. Once the system has been tested and debugged on the test cart (see Figures 2.6.10 and 2.6.11), it will be transferred to the crack sealing truck and integrated with all of the other systems. Testing and troubleshooting of the second generation prototype on the crack sealing truck is scheduled to begin in late November.

Figure 2.6.10 - Photo of test cart and integrated second generation VOC system prototype.

Figure 2.6.11 - Photo of test cart and integrated second generation VOC system prototype.

2.6.8 - Component Descriptions

2.6.8.1 - Fifth wheel

The fifth wheel subassembly is used to provide data to the VOC computer program for the purpose of tracking the position and orientation of the crack sealing truck. The fifth wheel subassembly consists of the following components:

- a wheel that rolls on the road surface and thus turns the rotary encoder,
- an encoder for converting the rotary input to digital, electrical outputs, and
- all linkage, fastening components, and electrical cables necessary for attaching the wheel and encoder to the crack sealing truck and VOC computer.

Refer to Figure 2.6.1 for a schematic illustration of the integration of the two fifth wheel subassemblies on the crack sealing truck. Complete detailed lists of parts and components necessary to build the second generation 5th wheel subassemblies are provided in Appendix F, drawings SHRP(VOC)M-A100, SHRP(VOC)M-A200, and SHRP(VOC)M-B100.

2.6.8.2 - Encoders

A simplified optical, rotary encoder consists of three major parts. These include:

- a disk with radial line slits (see Figure 2.6.10),
- a light source, and
- a light detector (see Figure 2.6.11).

As the disk rotates, light is transmitted between radial line slits to the light detector which generates a triangular-wave voltage output. This output is fed to a comparator that transforms it to a square-wave voltage. The square wave is then fed to a counter which is triggered by the leading edge of the square wave.

Two incremental pulse encoders were used as the position transducers, and provided information on the vehicle's incremental position and heading. To meet the encoder requirements specified below, two BEI encoders were purchased. The encoders have a resolution of 2500 pulses per revolution. This results in a position error of 0.02 inches and a heading error of 0.14 degrees per pulse. The encoders each output A, B and Z pulses.

ENCODER RESOLUTION (LINES PER REVOLUTION)	2500
MINIMUM DISTANCE RESOLUTION	0.0625" (1.588 mm)
ENCODER OUTPUT	5V
ENCODER SUPPLY VOLTAGE	5Vdc
ENCODER OUTPUT FORMAT	channels A , B and Z
ENCODER CABLES	shield, twisted pair
FIFTH WHEEL RADIUS	8" (203 mm)
TEMPERATURE	0-70 C
HUMIDITY	100% RH
VIBRATION	5-2000 Hz
SHOCK	20G

Table 2.6.1 - Encoder Requirements.

Figure 2.6.12 - Schematic Illustration of Encoder Disk with Radial Line Slits.

Figure 2.6.13 - Schematic Illustration of Encoder Light Source & Light Detector.

2.6.8.3 - Counter Card

A counter card is installed on the backplane of the computer and records the counter outputs of the encoders. Each encoder outputs an A, B and Z signals. The A and B channels of each encoder output the same frequency pulse with a 90 degree phase shift, and enable the counter card to detect if the vehicle is moving forward or backward. The Z signal enables the counter card to track the number of revolutions the wheels have turned. To meet the counter card requirements specified below, a Xycom 230 Intelligent Counter Module was purchased and installed on the VME computer backplane. The Xycom counter card has eight thirty-two bit counters.

MINIMUM NUMBER OF COUNTING CHANNELS	6 up and down channels
BUS COMPLIANCE	VME compatible bus
COMPUTER	Heurikon HK68/VE3
MINIMUM INPUT FREQUENCY	2kHz
POWER REQUIREMENTS	5V
TEMPERATURE	0-65 C
HUMIDITY	95% RH
VIBRATION	2.5 G peak acceleration
SHOCK	30G peak acceleration

Table 2.6.2 - Counter Card Requirements.

2.6.9 - Second Generation 5th Wheel Assembly Design Drawings

The second generation 5th wheel assemblies are quite complex. From experience gained during the development, testing, and troubleshooting of the first generation prototype, it was apparent that substantial redesign of the second generation prototype was necessary to meet the functional specifications of the VOC system. The second generation 5th wheel assemblies are due to be delivered from the vendor on November 9. As is, modifications made to the second generation prototype should allow the VOC system to easily meet all of the necessary functional specifications.

All assembly and detail drawings for the second generation 5th wheel assemblies are provided in Appendix F.

2.7 - Component Performance Specifications

2.7.1 - Introduction

This section presents the performance requirements of the four primary system components on the automated sealing machine. These components are:

1. Crack sensing system.
2. Router.
3. Hot air lance.
4. Sealant applicator (and finishing tool).

Each of these system components interacts directly with cracks in the pavement. The net result of all components operating sequentially is the preparation of cracks and installation of sealant material into the prepared crack. This sequence closely follows the sequence of operations associated with conventional sealing methods.

1. Crack routing or sawing (optional).
2. Crack cleaning and drying.
3. Sealant application.
4. Sealant finishing.

The obvious differences are that, in conventional operations, crack sensing (locating the cracks in the pavement) is done by the equipment operators and sealant finishing is usually a separate operation that is performed after sealant application.

The performance requirements of each of the four system components are presented in the following sections. Most of the requirements pertain to operational effectiveness (i.e., how well the system accomplishes its objective). However, production rate and equipment durability requirements are also included.

2.7.2 - Crack Sensing System

The objective of the sensing system is to locate and store crack positions, and accurately measure crack widths so that automated crack preparation and sealant installation can be properly performed. Any errors incurred in sensing the position of the crack will likely create problems in subsequent operations. Hence, the crack sensing system is perhaps the most critical system in the automated operation.

The sensing system consists of two components that work in conjunction with one another. The Vision Sensing System (VSS) uses a video camera and an image processor to locate the approximate position of a possible crack. The Local Sensing System (LSS) uses a laser vision sensor to scan the area around the potential crack location identified by the VSS and confirm or reject the presence of the crack. In addition, the LSS provides more precise crack position information to compensate for inherent inaccuracies in the VSS.

There are many performance requirements that are placed on the automated sensing system. Table 2.7.1 lists the specific requirements related to operational effectiveness. In general, the system must be able to detect unsealed transverse cracks and define their position and dimensions to an accuracy of 0.2 in (5.1 mm). The cracks that are identified should meet the agency's criteria for crack sealing in terms of width, length, and density. This complex sensing process must operate rapidly enough to allow the automated sealing unit to move continuously down the roadway at a rate of at least 2 mi/hr (3.2 km/hr). From a durability standpoint, the functioning equipment must not be adversely affected by prevailing conditions (i.e., temperature, dust, and flying debris).

Performance Indicator	Requirement
Resolution Along Scan	0.063 in (1.59 mm)
Vertical Resolution	0.063 in (1.59 mm)
Accuracy of Crack Position	0.2 in (5.1 mm)
Field of View	4 in (102 mm)
Humidity	0 to 85 percent
Operating Temperature	32 to 160 ^{o}F (0 to 71 ^{o}C)
Sensor Must Function Properly When Exposed To	Wind and Sunlight Dusty Environment Surface Color Variations Moisture on Pavement Debris in Cracks Road Surface Height Variations Temperature Variations Electromagnetic Interference
Sensor Must Distinguish Between Actual Cracks and	Previously-Sealed Cracks Oil Spots Shadows

Table 2.7.1- LSS requirements.

2.7.3 - Router

The objective of the router component is to create a widened channel along the crack surface. This channel permits the sealant to be placed in a uniform shape and also helps to ensure that sufficient quantities of the sealant material are applied to the crack. Both result in increased performance potential; with penetration improving adhesion and shape uniformity enhancing flexibility.

There are four essential performance requirements for the automated rotary-impact router, in addition to equipment durability. These requirements are:

1. Must accurately follow cracks.
2. Must not inflict significant damage to the pavement surround.
3. Must form channel of consistent depth (and width) along same crack and among individual cracks.
4. Must maintain sufficient cutting rate.

When a router does not accurately follow a crack, the result is two adjacent channels (one formed by the router and the other the existing crack) and a weakened pavement segment in between. In the case of conventional impact routers, missed cracks are usually due to operator error. Cracks missed by the automated impact router, however, will likely be the result of either inadequate maneuverability, inaccurate crack position information, or jostling of the router component during operation. In any case, it is important that the router accurately follow cracks over at least 97 percent of the total crack length.

While rotary-impact routers generally satisfy the above objective, they have a tendency to inflict additional damage to the pavement in the form of spalls or fractures. This is because the impact action of the router bits tears rather than cuts material away from the pavement. Hence, serious pavement surround damage is more likely to occur when router bits are dull, pavement temperatures are low, or the AC surface course contains large coarse aggregate. For the automated impact router, such damage must be kept to less than 3 percent of the crack length.

Routed crack channels are generally created for the purpose of injecting sufficient sealant material into the crack. However, the dimensions, or shape, of the channel are often selected to provide optimal flexibility of the sealant material. Where the shape of the channel varies from the optimal shape, the potential performance of the sealant material is reduced. Thus, it is important that the cutting dimensions (primarily depth) are consistently maintained to an accuracy of ± 0.2 in (5.1 mm).

The range in cutting dimensions of the automated router component were selected based on conventional and innovative rout profiles. These include 0.5 x 0.5-in (12.7 x 12.7-mm), 0.75 x 0.75-in (19.1 x 19.1-mm), and 0.2 x 1.5-in (5.1 x 38.1-mm) channels. The prototype router must be capable of producing channels up to 2.25 in (57.2 mm) wide and 0.85 in (21.6 mm) deep.

Finally, while meeting all of the above requirements, the router must also maintain a production rate that corresponds with the specified 2 mi/hr (3.22 km/hr) forward rate of the automated sealing unit. The required operation rate along the crack is ____ ft/min (__ m/min).

[NOTE: items left blank in previous paragraph to be determined for final report.]

2.7.4 - Hot Air Lance

The hot air lance is the main component in the heating, cleaning, and debris removal (HCD) system. It is an important component of the crack preparation process because it is responsible for instantaneously drying any moisture in the crack and heating the crack periphery. Both actions greatly improve the bonding potential of the sealant to the sidewalls of the crack channel.

The heat lance provided on the automated sealing machine is unlike conventional heat lances because the heating capabilities and the supply of air are considerably different. Conventional heat lances typically deliver air heated to temperatures between 2000 and 3000 ^{o}F (1095 and 1650 ^{o}C). These temperatures are much higher than the 1600 ^{o}F (870 ^{o}C) capacity of the automated hot air lance. Conventional models also produce airblast rates in the vicinity of 150 ft^3/min (4.26 m^3/min) at pressures around 90 lb/in^2 (621 kPa). This compares with 400 ft^3/min (11.34 m^3/min) at 50 lb/in^2 (345 kPa) for the automated hot air lance.

Since the automated heat lance is designed to only dry and heat the crack channel, and not clean it, there are three main performance requirements for this device. First, it must adequately remove any moisture that might exist in the crack channel. Successful application of the automated heat lance will result in a channel that is dry to the touch and hot-applied sealant that does not bubble shortly after installation.

Second, the heat lance must not overheat the AC surface. Overheating not only results in brittle asphalt concrete along the crack periphery, but also produces an oxidized grit that can adversely affect adhesion by the sealant material.

Finally, while satisfying the first two requirements, the heat lance must operate along the crack at ft/min (__ m/min) in conjunction with the 2 mi/hr (3.22 km/hr) forward rate of the automated sealing unit. In conventional sealing operations, production is occasionally constrained by the heat lance operation. However, this is primarily because the heat lance is also used for cleaning.

[NOTE: items left blank in previous paragraph to be determined for final report.]

2.7.5 - Sealant Applicator and Squeegee

The final step in the automated sealing process is sealant application and finishing. The system component devised for performing this step is a combination sealant dispenser and squeegee, capable of rapidly applying and shaping sealant in various configurations (e.g., band-aids of varying widths).

From a performance standpoint, the applicator unit must be able to accomplish four tasks. First, in order to produce the desire sealant configuration, an adequate amount of material must be applied to the crack and the proper strike-off must be made. The finished surface should, for all practical purposes, be within 0.0625 in (1.6 mm) of the desired level.

Second, the crack channel must be filled from the bottom up to prevent air from being trapped under the material. Signs of entrapped air include immediate bubbling of the sealant and localized sagging of the material.

Third, and perhaps most importantly, the hot-applied sealant material must be applied to the crack at the manufacturer's recommended application temperature. The actual application temperature should be within ± 5 ^{O}F (2.8 ^{O}C) of the recommended application temperature in order to achieve optimal performance.

Finally, to stay in stride with the forward rate of the automated sealing unit, the applicator must operate individually at a rate of ___ ft/min (__ m/min).

[NOTE: items left blank in previous paragraph to be determined for final report.]

2.7.6 - *Summary*

It is apparent that in order for the automated sealing machine to achieve its objective, each system component will have to execute its portion of the overall sealing operation precisely and at a relatively high speed. Thus far, prototype component testing has indicated good potential for doing so.

Performance of both the overall and individual operations will be evaluated in a field demonstration trial. Various sections of highway will be used to study the operation effectiveness, production, and durability of each component under various conditions. Each test will be closely monitored and documented, and the results will be analyzed to see if performance requirements were met. Further details about the field demonstration trial are provided in Chapter 5.

3

Integrated Longitudinal Crack Sealing System

3.1 - Method of Operation

The longitudinal crack sealing machine consists of the Longitudinal Robotic Positioning System (LRPS), the Local Sensing System (LSS), the Applicator and Peripherals System (APS), and a control computer. The detailed descriptions of the LRPS, the LSS, and the APS are given in Chapter 2, and the role of the control computer will be described below. Here, the interaction between these components during the operation of the longitudinal machine is described.

Unlike the general machine, there is no need for a global vision system to identify the location of the cracks when using the longitudinal machine, since the nature of the cracks addressed by the longitudinal machine is much more restricted. In addition, there is no need to pre-plan a path for the longitudinal machine. During operation of the longitudinal machine, the driver of the vehicle merely needs to maintain the center of the LRPS near the position of the longitudinal crack to be sealed. This can be done visually using a pointing device, or using a camera and a monitor.

The position of the LRPS is controlled by a hydraulic actuator, with the loop closed by a position transducer located on the hydraulic cylinder. This controller is capable of accurately positioning the center of the LRPS in the lateral direction, i.e. perpendicular to the centerline of the cart. The longitudinal motion of the system is dictated entirely by the motion of the vehicle.

The LSS is mounted as part of the crack sealing tooling for the LRPS. This sensor provides an error signal, which represents the offset of the center of the LRPS to the center of the longitudinal crack. This signal is used by the control computer to modify the desired position input for the closed-loop control system. This signal is then communicated to the actual closed-loop controller using an RS-232 serial communication line. With this updated position command, the LRPS can then track in to the actual crack position.

If, due to either large motion of the crack or the crack sealing vehicle, the longitudinal crack moves out of the 4 inch field of view of the LSS, the LSS will issue a saturated error signal, which will then drive the position command in the direction that the crack was last seen. In most cases, this will drive the LRPS back to the crack, and then the closed-loop control to follow the crack can proceed. If the LSS does not detect a crack again within the range of motion of the LRPS, then an error signal can be generated to the ICU, which will then handle the situation by sending a signal to the operator.

The ICU will be used to maintain high-level control of the LRPS, and to receive status information from the control computer and the LSS. The ICU will function to initiate and terminate the sealant flow and the router. However, the LRPS, LSS and the control computer have been designed so that they can operate as a stand-alone unit, without the assistance of the ICU.

Chapter 2 included detailed figures and description of the various configurations of the LRPS, and the interested reader is referred to that chapter for more information.

4

Integrated General Crack Sealing System

4.1 - Method of Operation

The general crack sealing machine is composed of the Vision Sensing System (VSS), the Integration and Control Unit (ICU), the path planning module (which resides on the ICU), the Vehicle Orientation and Control (VOC) system, the general Robot Positioning System (RPS), the Applicator and Peripherals System (APS), and the Local Sensing System (LSS). The detailed descriptions for these components are given in Chapter 2. In this section, the interaction between these components during operation of the general machine is described.

As the vehicle moves down the road, the VSS will buffer an image of the roadway for 20 feet, approximately half the length of the truck. The VSS identifies potential crack locations using the algorithm described in Section 2.2. The output of the VSS consists of row and column numbers for the tiles in the current frame where the VSS located a potential crack, as well as the integer valued direction number determined by the algorithm. This data is translated into real-world coordinates using information from the VOC; this will be described in more detail later. The VSS data is not in a from that is usable by the RPS, as there is no relationship between the identified crack points as output by the algorithm. The path planning algorithm will convert the data into a format that is useful to the RPS. The VSS sends this information to the ICU over an Ethernet connection, and then begins to buffer up the next frame of data.

The ICU is the main coordinating process for the general crack sealing machine. All data for the various subsystems is routed through the ICU, and the ICU issues signals to the subsystems and handles signals received from the various subsystems. The ICU will take in the data from the vision system, initiate the path planning process, coordinate the transformation of the planned paths with the VOC data, and issue the paths to the RPS when the identified cracks are in the manipulator workspace. The ICU will also coordinate with the RPS by obtaining information regarding the current status of the crack sealing process. This status information is based mainly on the readings from the LSS, which is used to verify the planned path based on the VSS data, as well as to verify the presence and location of actual cracks. The ICU does not communicate directly with the LSS; instead, it receives LSS data indirectly by way of the RPS.

Once the VSS frame data has been received, the ICU notifies the path planning algorithm that data is ready. The path planning algorithm is part of the ICU, but is a separate process that runs in parallel with the main ICU routines. Path planning is used to clean up the VSS data, form connections between isolated but possibly connected crack segments, and form the data points into ordered sets that constitute reasonable paths for the RPS to follow to complete the crack sealing process. The path planning process begins by forming the VSS data into a matrix which represents an image of the road as identified by the VSS algorithm, and filters the data to clean it up. Then the planner identifies end points of individual segments and attempts to form connections between isolated points according to an empirically determined distance which represents the distance that actually connected crack segments may be separated by when processed by the vision system. The connections are made by placing a circular growth region, with a radius equal to half the above empirically determined distance, around each end point in the frame data. If segments are separated by less than the above distance, then they will be connected after this phase of the planning algorithm. The path planner next 'thins' this data to bring it back to images of cracks, using a thinning algorithm to strip out points in the data set while maintaining the general shape and connectivity of the image. After this, the path planner forms a data structure that represents all the connected crack paths for the entire frame of VSS data. When the ICU passes the coordinates of the current manipulator workspace to the path planning algorithm, it then extracts a data structure representing the connected crack paths for that workspace. This data is then transformed using information from the ICU, and passed to the RPS for sealing of the cracks. For a more detailed description of the path planning algorithm and its relation to the rest of the Integrated General Crack Sealing System, see the paper "Path Planning for Robotic Applications in Roadway Crack Sealing" by T. A. Lasky and B. Ravani. A copy of this paper is included in an appendix.

The VOC system tracks the position and orientation of the crack sealing vehicle relative to a world coordinate reference frame. As the VSS identifies potential crack locations, the VOC uses the position of the truck relative to the world frame, in conjunction with known and fixed transformations between the subsystem reference frames on the vehicle, to mark the position of the crack locations with respect to the world reference frame. At any subsequent time, the VOC can transform this point in the world reference frame into the RPS reference frame, using the known and fixed transformation from the vehicle frame to the RPS frame, along with the current transformation from the world frame to the vehicle frame. Thus, the paths that are established by the path planning algorithm, since they are essentially collections of points identified by the VSS, can be transformed into the RPS reference frame so that the RPS can guide its tooling along this path to seal the cracks.

The RPS takes the planned and transformed path from the ICU, and uses this path to position the tooling to prepare and seal the identified crack. The communication between the ICU and the RPS is over an RS-232 serial line. The RPS will initially use the pre-planned path to get to the start of the crack, and will subsequently use this path as a nominal position trajectory. Using the LSS sensor, which is mounted on the manipulator tooling, the RPS can verify the presence or absence of the identified crack. This is required for at least two reasons. First, the VSS cannot distinguish between cracks, oil on the roadway, and previously sealed cracks. As long as the image has the appropriate light/dark histogram to pass the VSS comparison algorithm, it will be identified as a crack. Only the LSS, with its ability to measure the height profile of the road, can actually verify the presence of the crack. Second, there will be accumulated error introduced by the VSS, the path planning algorithm, and the VOC. Without any local feedback of the position of the crack, the RPS would have no way to adjust for this accumulated error. The RPS will use the orientation information from the planned path without modifying it, as the LSS information is insufficient to determine a good measure of the crack orientation. The RPS can use this orientation information to align the tooling with the crack, the offset error of the tooling from the center of the crack can be identified with the LSS, and the RPS can modify its trajectory in a closed-loop fashion to eliminate this error. In the case that the accumulated error exceeds the range of the local sensor, the RPS can enter a search mode, in which it scans perpendicular to the assumed direction of the crack, until it locates a crack. The RPS will pass signals back to the ICU indicating the status of its operation. For example, the RPS can pass the LSS error signal back to the ICU periodically, and the ICU can monitor this information over time, and use it to identify the need for system or component recalibration.

5

Machine Testing

5.1 - Detailed Test Plan

[NOTE: This chapter is in very rough, draft form. It is envisioned that a more detailed test plan will be developed prior to the internal demo that Caltrans has planned for December 17, 1992.]

In order to fully evaluate the operational performance of the automated sealing machine as a complete unit, it must be field-tested on an appropriate section of pavement. Since the H-107a research effort has focused heavily on automating the most difficult sealing operation, AC transverse crack sealing, the test pavement section must be asphalt-surfaced and must contain a sufficient number of transverse cracks for a variety of tests.

Designing and arranging a field demonstration trial can be a long and difficult process. The first step is to identify the goal and objectives of the experiment. In general terms, the objective of the test plan is to evaluate the ability of the individual components as well as the system as a whole to seal cracks. Thus the testing must consist of:

- Microtesting (of the individual components).
- Macrotesting (of the overall system).

There are generally many factors that must be considered for each type of testing. Decisions must be made as to which factors will be evaluated in the field trial given the constraints of costs, time, personnel availability, weather, and so on.

Once a field testing plan has been formulated, the search can begin for potential sites that accommodate the specific features in the test plan, as well as any other desired characteristics. In the event that multiple potential sites are located, they may be ranked in order of suitability. Permission to use the most suitable site will be sought from the agency having jurisdiction over the pavement facility.

Prior to conducting the field trial, an evaluation plan must be developed in order to assess the performance of the various tests. Field documentation forms and equipment must be prepared for collecting the performance data.

As the automated crack sealing equipment has developed, different components of the overall system are farther advanced than others. Given that SHRP will close its doors in early 1993, it will not be possible to complete the development of equipment with full functionality. At this point, the technology associated with longitudinal crack sealing equipment this crack sealing is the most mature. The hardware and software to perform transverse crack sealing in AC pavements are in prototype condition, and it is believed they will be ready for controlled testing on a component by component basis in early 1993. A controlled test of the integrated system can also be performed at that time.

To address this uneven development, it is believed that an appropriate test plan consists of a process which takes into consideration the current maturity of the various systems. The test plan described below accomplishes this.

The following sections discuss the important aspects associated with designing and arranging the field demonstration trial for the automated sealing machine.

5.1.1 - Transverse Crack Sealing

The test of the prototype transverse crack sealing operation will be conducted in a semi-controlled environment in recognition of the current status of the equipment. The purpose of the test will be to document and demonstrate the capabilities of the prototype equipment, rather to show that the equipment is ready for commercialization. The test will include both component-by-component and overall system checks.

5.1.1.1 - Vision System

The evaluation of the vision system must address several of the system's capabilities. Are cracks of the proper width identified (ignoring cracks that are both wider and narrower)? Are cracks of the proper length identified (ignoring cracks that are too short)? How well does the sensing system follow a meandering crack? What is the ability of the sensing system to differentiate between cracks and non-cracks? It is believed that this test is best done in a section of pavement with known attributes. This includes a range of crack widths and lengths less than, in range, and greater than the system specifications. It will also include cracks that approximately follow the path of a transverse crack and cracks that change direction over a short distance. Finally, a test of the discriminating abilities of the sensing system will include operating it over sealed cracks, oil stains, and other surface markings that might be confused with cracks.

This test section can be located anywhere there is sufficient pavement to create a suitable test. It can include existing cracks if they meet the criteria, but will most likely consist of a number of manufactured cracks that will test the system's abilities. It will also include the placement of a number of pavement markings intended to test the systems' ability to discriminate.

The final test plan will provide the details of the number of tests required, how the test of the vision system will be set up, and how the results will be measured and presented.

5.1.1.2 - Router/Debris Removal

The router (and the vacuum system incorporated with it) operates in conjunction with the vision system. The field test of this component must therefore consider both the interaction between the router and the pavement, as well as the way in which the vision system and router perform together.

Considering the routing system alone, the test must evaluate whether the router creates the desired size and shape of reservoir, if the routing process causes additional damage to the pavement, and if the reservoir is left clean enough to be sealed. When the router is operating under the guidance of the vision system, additional checks include: does the router find the cracks that are selected to be sealed, does the router correctly rout the cracks, and are there crack paths that the equipment can not follow?

Again, considering the current stage in the development of the equipment, it is recommended that this test be performed in a semi-controlled environment. The purpose of the test is not to evaluate the overall robustness of the equipment, but rather to assess its current abilities and highlight what future work is needed to proceed beyond the prototype stage.

5.1.1.3 - Sealant Applicator and Peripherals

This subsystem consists of the sealant applicator and the storage and heating reservoir. For the sealant storage and heating reservoir, the following capabilities must be evaluated:

- Are the properties of the sealant left stored in the reservoir essentially unchanged after being subjected to the heat of the sealant reservoir?
- How much time is required to bring the sealant to the manufacturer's recommended application temperature?
- Is the sealant maintained at sub-critical temperatures as the volume of the storage reservoir changes?
- How is the heat monitored? How accurate are the readings?

For the sealant applicator, the following capabilities are of interest:

- Does the applicator apply sealant in the cracks that are selected for sealing?
- Is the sealant applied according to the desired configuration?
- Is the sealant tooled as intended?
- Is sufficient sealant applied?
- What is the effect of sealing the pavement on the overall ride (in other words, does the sealant cause increase roughness)?
- What is the long-term performance of the sealed pavement?

5.1.2 - Longitudinal Crack Sealing System

The prototype of the longitudinal crack sealing system is further advanced than that of the transverse crack sealing system and is therefore able to be subjected to a more rigorous and comprehensive field test. This is a result of the fact that the longitudinal crack sealing system can operate independently of the vision system. Furthermore, the operation, which progresses along a straight, uninterrupted longitudinal path, is the least challenging to the system's two major components.

The field test of the longitudinal crack sealing system should test the following operations and subsystems:

- Speed of sealing.
- Long-term performance comparison with conventionally performed sealing.
- Sealing alone.
- Routing and sealing.
- Routing, vacuuming, and sealing.
- Hot air lance.

[NOTE: Complete section describing the test section. They will be 500 ft (152 m) long, there will be a partial factorial experimental design, with replicates. Performance measurements will be documented before the test is performed.]

5.1.3 - Ideal Test Plan

Ultimately, the transverse crack sealing system will need to be subjected to a field test on an actual pavement. Such a test is better able to assess the system's robustness, operating speed, consistency, productivity, safety concerns, and so on. This section addresses the test plan to be performed when the system is ready for complete testing.

To satisfy testing of the most essential performance attributes, the following features are desired in the test site:

- Close proximity to development facility.
- Asphalt surfaced pavement (AC flexible or AC/PCC composite) section at least 1 mi (1.61 km) in length.
- Four-lane facility with moderate traffic (7500 to 20,000 ADT) levels and 5 to 10 percent trucks.
- 12-ft (3.7-m) lane widths.
- Working, transverse thermal or reflection cracks.
    - Average crack width between 0.188 and 0.5 in (4.76 and 12.7 mm).
    - Average full-width crack spacing between 25 and 75 ft (7.6 and 22.9 m).
    - Some deteriorated cracks (i.e., secondary cracks, cupping, lipping) present.
- Flat and moderate grades (0 to 4 percent).
- Moderate quantities of additional distress.
- Adequate safety features (i.e., full outside shoulders, good sight distance).

Additional features may become necessary should other performance considerations be desired.

5.1.4 - Identification of Proposed Test Site

As a means of locating potential test sites, a 1- or 2-day pavement inspection trip will be made. Various pavement facilities will be examined to see how they meet the criteria presented in the previous section. Those facilities identified as having conformed to most or all of the requirements will be rated for overall appropriateness using a quantitative analysis procedure. This is done by assigning different weights to each of the desired characteristics, rating the individual characteristics of each potential test site, and computing a mean overall rating for each site. The highest rated test site would be the prime candidate for conducting the field demonstration trial. Permission would then be sought from the appropriate agency to use the site.

5.1.5 - Controlled Conditions and Factors

Thorough examination of the performance capabilities of the automated crack sealing machine necessitates the use of several trial sections within the test site. The exact number of trial sections depends on:

- The perceived importance of the various performance factors.
- How efficiently a testing matrix can be formulated.
- Time and financial constraints.
- Limitations presented by test site length.

In order to evaluate the effectiveness of each system component, test trials will be conducted whereby different sets of components are operated. For instance, to investigate the accuracy of the router component, just the sensing system, router, and vacuum would be operated. Likewise, to evaluate the adequacy of the cleaning provided by the vacuum, the same three systems would be operated. Table 5.1 lists the component combinations to be operated for evaluating the effectiveness of each component.

In addition to these standard tests, the effects of several weather- and pavement-related factors on effectiveness will be studied, as shown in Table 5.2.

System To Be Evaluated	Components To Be Operated
Sensing System	1. Sensor, or 2. Sensor, Router, and Vacuum
Router	1. Sensor, Router, and Vacuum
Debris Removal (Vacuum)	1. Sensor, Router, and Vacuum
Hot Air Lance	1. Sensor and Hot Air Lance, or 2. Sensor, Router, Vacuum, and Hot Air Lance
Sealant Applicator and Squeegee	1. Sensor, Hot Air Lance, and Applicator-Squeegee, or 2. Sensor, Router, Vacuum, and Applicator-Squeegee, or 3. Sensor, Router, Vacuum, Hot Air Lance, and Applicator-Squeegee

Table 5.1 - Evaluation of system components.

5.1.6 - Evaluation Procedures

Performance evaluation techniques should, for the most part, be straightforward. Simple inspections and various types of measurements will usually be sufficient in assessing the effectiveness of the individual operations. In addition, production will be timed over established distances to determine rates for both the system components and the entire automated sealing unit. Table 5.3 lists suggested evaluation procedures for the various system components. In controlled condition sections (i.e., sections where weather- and pavement-related factors are investigated), effectiveness will be measured using the same procedures shown in Table 5.3.

5.2 - Testing Results

The information collected from the field demonstration trial will be analyzed primarily during the trial so that any minor equipment adjustments can be made for prompt retesting. The overall results of the test will be analyzed and compared with conventional sealing operations in order to determine the practicality of the machine as a maintenance tool. Additional factors that will be considered as part of the analysis include costs, short-term effectiveness, and long-term performance.

Effectiveness of Operation	
Factor	System Evaluated
Air Temperature	Sensor, Router
Wind	Sensor
Intensity of Light	Sensor
Crack Width	Sensor, Router
Crack Deterioration Level	Sensor, Router
Pavement Moisture	Sensor, Vacuum, Hot Air Lance

Table 5.2- Weather- and pavement-related factors affecting system performance.

System Component	Performance Item	How Evaluated
Sensing System	Accuracy in Defining Crack Position	Compare to Results of Manual Identification
	Accuracy in Determining Crack Dimensions	Compare Selected Cracks to Those Selected Manually
	Surface Distinctions	Visual Inspection
	Speed	Time
Router	Accuracy in Following Crack[2]	Measure Percent of Missed Crack
	Inflicted Damage to Pavement Surround[2]	Measure Percent of Fractured or Spalled Pavement
	Consistent Channel Dimensions	Measure
	Speed	Time
Hot Air Lance	Drying Effectiveness	Visual/Touch Inspection
	Proper Heating	Visual/Touch Inspection
	Speed	Time
Sealant Applicator and Squeegee	Desired Seal Produced	Measure
	Proper Filling Procedures Followed	Visual Inspection
	Sealant Dispensed at Recommended Application Temperature	Measure with Thermometer Probe
	Speed	Time

Table 5.3- Evaluation procedures for system components.

5.2 - Test Results

5.2.1 - Introduction

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[2] Original crack pattern shall be mapped by hand or reproduced using casting material.

5.3 - Machine Performance Specifications

5.3.1 - Introduction

The current prototype sealing machine is designed to seal transverse and longitudinal cracks in AC pavements. Critical to its acceptance and integration into highway maintenance operations are the rate at which the machine can operate, the quality of the results of the sealing operation, and the capabilities and limitations of the system. The impact of the costs of the equipment on its acceptance is addressed elsewhere.

5.3.2 - Production Rates

The production rate for the prototype sealing machine is related to the speed of the vision and local sensing systems, the rate of each preparation and installation attachment, the distance between transverse cracks, and factors that relate to the individual characteristics of the system components. As noted previously, current test results indicate that the slowest of the operations is the rotary impact routing, with a rate of ___ ft/min). Since the slowest operation controls the rate of production, the maximum sealing rate of the automated sealing machine is ___ ft/min). The tested or estimated speeds of each component of the prototype crack sealing machine are listed in Table 5.4. These rates are based on the assumptions that the cracks are routed, cleaned with hot-compressed air, and sealed with hot-applied sealant. The table also contains estimates of sealing rates using the above preparation procedures and current conventional manual methods. It should be noted that the crack sealing policies of highway agencies differ considerably, and those agencies that omit one or more of these steps will experience a faster production rate. [NOTE: items left blank in previous paragraph to be determined for final report.]

Rates and Requirements [3]	Transverse Cracks		Longitudinal Cracks	
	Current Methods	Prototype Equipment	Current Methods	Prototype Equipment
Sealing Rate, ft/min	12 to 15	176	12 to 18	176
Travel Rate, mph [4]	0.25 to 0.45		0.14 to 0.21	2.0
Workers Required	6	2	5	2

Table 5.4 - Comparison of sealing rates and requirements.

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[3] 1 ft = 0.3048 m; 1 mi = 1.609 km

[4] Distances between transverse cracks are assumed to range from 25 ft (7.6 m) and 50 ft (15.2 m).

As the table indicates, the sealing rate of the prototype equipment is __ times that of current sealing practice. It is expected that the sealing rate can be increased __ more times with a few modifications. In addition, the number of workers required to complete the sealing operation, apart from traffic control workers, is reduced from 6 to 2 when the prototype equipment is used. The great improvements in production rates, labor requirements, and worker safety are readily apparent.

5.3.3 - Quality of Performance

The quality of sealant installation can be rated on the basis of several factors. These factors, listed below, are related to the routing, the cleaning, and the installation operations.

- Accuracy of the router positioning.
- Conformance of the routed reservoir depth.
- Pavement damage caused by the routing operation.
- Cleanliness of the reservoir prior to sealant installation.
- Damage to the pavement from the hot, compressed-air blasting.
- Consistency of the sealant surface level.

A good quality, manually controlled routing operation can follow a meandering crack, staying over the crack for more than __percent of the crack length. Tests of the prototype machine indicate that the visual and local sensors can be used to keep the 0.5-in (13 mm) wide router over a meandering 0.125-in (3 mm) wide crack for more than __ percent of the crack length. (Revise as necessary)

If travel speeds are high, a router can tend to ride out of a crack, resulting in inconsistent reservoir depths. The prototype router has been able to maintain router depth within 0.__ in (__ mm) of the design depth at a speed of __ mph (__ km/hr).

Dull routers blades, blades rotating at low speeds, low pavement temperatures, or large coarse surface aggregate can result in cracking and spalling of the crack edges. An experienced router operator using a router that has sharp blades can typically keep spalling to less than __ percent of the crack length. The prototype router is expected to perform comparably.

The cleanliness of the crack reservoir and the surrounding pavement can significantly affect the performance of crack sealants. Good quality manual sealing operations allow more than __ minute delay between hot airblasting and sealant installation. This permits the pavement surface to cool, possibly allowing moisture to condense on the crack sidewalls. It also allows time for dirt and debris from the surrounding pavement to return to the sealant reservoir. The automated sealing machine must completely remove dirt, dust, and oxidized asphalt grit from the crack sidewalls. With the automated sealer, the time delay between cleaning and sealant installation should be significantly reduced.

[NOTE: items left blank in previous paragraph to be determined for final report.]

Overheating an AC surface with hot, compressed air can scorch the asphalt binder, resulting in brittle asphalt concrete that is less compatible with hot-applied sealants. Indicators of overheating are a darkened AC surface and an oxidized asphalt grit that forms on the pavement surface. The automated heat lance, when performing properly, should maintain the desired temperature without damaging the AC pavement due to high or prolonged heating.

When sealant material does not completely fill a sealant reservoir or has settled, sand and debris can collect in the reservoir and the sealant can oxidize more quickly. Underfilled reservoirs can result from an insufficient amount of sealant being placed in the reservoir or from sealant sinking into the underlying crack. Overfilling the reservoir can result in unsightly sealant remaining on the pavement surface. The automated sealant applicator should maintain the surface of the sealant even with the pavement surface without underfilling or overfilling the reservoir.

Of course, overall performance is measured by long-term monitoring of the sealed pavement. It is expected that the use of automated systems of crack and joint sealing will not result in a significantly longer lasting sealant system. Such repairs should, however, last as long as the best crack sealing jobs done manually.

5.3.4 - Capabilities

The prototype automated crack sealing machine is capable of sealing longitudinal and transverse cracks in AC pavements. It is not designed to seal fatigue cracks, which is indicative of a major structural distress requiring rehabilitation. Neither is the automated crack sealing equipment designed to be able to seal random block cracking that is closely spaced.

The vision and local sensors are able to detect longitudinal and transverse cracks in AC pavements that have widths greater than 0.2 in (5 mm). When a secondary crack or branch is encountered, the longitudinal machine will continue sealing the crack that is closest to the direction of the current crack. In a similar situation, the general (transverse) crack sealing machine will use pre-planned path information to resolve the branching decision.he longitudinal machine will tend t

The specially designed router is capable of producing a sealant reservoir up to 0.85 in (22 mm) deep and up to 2.25 in (57.2 mm) wide. It can cut in any direction, reversing direction quickly. This allows the routing operation to proceed more rapidly.

The hot-airblasting system is able to heat an AC pavement to 250 ^{o}F (121 ^{o}C) at a depth of 0.5 in (13 mm) within __ seconds when the ambient temperature is above 50 ^{o}F (10 ^{o}C). Within __ seconds, the machine applies the sealant, reducing the effects of cooled pavement.

Currently, the sealing machine is designed to install hot-applied sealant material with a band-aid of variable width. The sealant heating chamber is capable of holding __ gal (__ l) of sealant, heating a full container of sealant to application temperature within __ hr at an ambient temperature of 50 ^{o}F (10 ^{o}C). It can maintain sealant at an application temperature of 380 ^{o}F (193 ^{o}C) while dispensing at a rate of __ gal/hr (l/hr).

[NOTE: items left blank in previous paragraphs to be determined for final report.]

6

Commercialization Issues

6.1 - Introduction

This section will detail out a basic summary of the current research team findings, as they relate to the issues associated with commercialization. Specific mention will be made of the team's use of modular design, the subsequent value that modularity has lent to accommodating equipment evolution (with changes in technology), and the split out of the longitudinal machine from the general machine.

A statement will be made as to the standard convention of "commercialization" implementation and analysis in industry, and the differences that are presented by the research team vs a standard manufacturing company.

[THIS SECTION WILL BE EXPANDED UPON LATER WHEN FURTHER DEVELOPMENTS AND TEST CONCLUSIONS CAN BE INTEGRATED INTO THE ISSUES FOR COMMERCIALIZATION.]

6.2 - Approach and Assumptions

This section will address the approach taken to evaluate commercialization issues as a function of the differences between a standard manufacturing facility and the research team. Included in this section will be an annotated outline of a marketing plan and a market research plan. Those specific elements that were in budget and scope of the research team's effort will be identified and reported on in detail. Suggestions for effective continuation of the marketing plan/market research plan will be detailed in the section "Future Issues", and referenced as such here.

In the industrial community, commercialization is most often defined as the "launching step" or implementation of a marketing strategy/plan. Heavy emphasis is placed on organization structure and the management talent necessary to implement the strategy. Emphasis is also given to follow up activities such continued product debugging, production cost control, and QA/QC, etc. In an effort to meet the needs of the FHWA/SHRP program with regards to this research project, an example of an annotated marketing plan is provided below. This plan approach was evaluated to see what items commonly found in industry could be addressed by the research team in an effort to reduce follow-on work required by the FHWA. Where it was determined that a contribution could be made or that there was a requirement to fulfill in completing this contract, amplifying material is provided under each subheading.

6.3 - Marketing Plan.

To follow is an outline of the section as it will appear in the final report.

I. Executive Summary -- an overview of the entire plan, including a description of the product or service, the differential advantage, the required investment, and the anticipated sales and profits.

II. Table of Contents

III. Introduction -- What is the product or service? Describe it in detail and explain how it fits into the market.

IV. Situational Analysis --
  A. The Situational Environs
    1. Demand and demand trends. [what is the forecast demand for the product: is it growing or declining? who is the decision maker? the purchase agent? how, when, where what, and why do they buy?]
    2. Social and cultural factors.
    3. Demographics
    4. Economic and business conditions for this product at this time and in the geographical area selected.

5. State of technology for this class of product. Is it high-tech state-of-the-art? Are newer products succeeding older ones frequently (short life-cycle)? In short, how is technology affecting this product or service?
6. Politics. Are politics (current or otherwise) in any way affecting the situation for marketing this product/service?
7. Laws and regulations. [what laws or regulations are applicable here?]

B. The Neutral Environs

1. Financial environment. [how does the availability or unavailability of funds affect the situation?]
2. Government environment. [is current legislative action in state, federal, or local government likely to affect your plans?]
3. Media environment. [what's happening in the media? does current publicity favor this project?]
4. Special interest environment. [aside from direct competitors, are any influential groups likely to affect your plans?]

C. The Competitor Environs

1. Describe your main competitors, their products, experience, know-how, financial human, and capital resources, suppliers, and strategy. Do they enjoy the favor with their customers? If so, why? What marketing channels do the competitors use? What are their strengths and weaknesses?

D. The Company Environs

1. Describe your products, experience, know-how, financial, human, and capital resources, and suppliers. Do you enjoy the favor of your customers? If so, why? What are your strengths and weaknesses?

V. The Target Market

Describe your target market segment in detail by using demographics, psychographics, geographics, life-style, or whatever segmentation is appropriate. Why is this your target? How large is it?

VI. Problems and Opportunities

State or restate each opportunity and indicate why it is, in fact, an opportunity. State or restate every problem. Indicate what you intend to do about each of them. Clearly state the differential competitive advantage.

VII. Marketing Objectives and Goals

State precisely the marketing objectives nd goals in terms of sales volume, market share, return on investment, or other objectives or goals for your marketing plan and the time needed to achieve each of them.

VIII. Marketing Strategy

Consider alternatives for the overall strategy; for example, for a new market penetration a marketer can enter first, early, or late, penetrate vertically or horizontally, and exploit three different niche strategies.

If the marketing strategy is at the grand strategy or strategic marketing management level, a market attractiveness/business capability matrix and product lifecycle analysis should also be made.

IX. Marketing Tactics

State how you will implement the marketing strategy(s) chosen in terms of the product, price, promotion, distribution, and other tactical or environmental variables. Note should also be made on how your main competitors are likely to respond when you take the action planned and what your response will be to avoid the threats and take advantage of the opportunities.

X. Implementation and Control

Calculate the break-even point and make a break-even chart for your project. Compute sales projections and cash flows on a monthly basis for a three-year period. Determine start-up costs and a monthly budget, along with the required tasks.

XI. Summary

Summarize advantages, costs, and profits and restate the differential advantage that your plan offers over the competition and why the plan will succeed.

XII. Appendices

Include all supporting information that you consider relevant.

6.4 - Marketing/Commercialization Research Plan.

The most common tool in industry for implementing a marketing plan or strategy is the marketing research plan. This tool is a detailed analysis of several of the components of the marketing plan. Specific emphasis is placed on understanding the market, narrowly defining the focus of the product development group, and providing data for an analysis of projected performance of the new product in the market. As before (with the market plan), an example of an annotated outline is offered with amplification where appropriate.

I. Project Title

II. Problem Statement

III. Define and Delimit the problem

Here the writer states the purpose(s) and scope of the problem. Purpose refers to the goals or objectives. Closely related to this is justification. Sometimes this is a separate step, depending on the urgency of the task. Scope refers to the actual limitations of the market research effort; in other words, what is not going to be investigated. Here is the point where the writer spells out the various hypotheses to be investigated or the questions to be answered.

IV. Outline

Generally, this is a tentative framework for the entire project by topics. It should be flexible enough to accommodate unforeseen difficulties, show statistical tables, in outline form, and also show graphs planned. Tables should reflect the hypotheses.

V. Method and Data sources

In order to provide the greatest insight possible as to the potential market for these machines, a questionnaire was developed that was issued over the Internet system to the 46 state DOTs that are currently connected. This questionnaire was developed to determine the level of interest of the respective state DOTs, the type of issues that would concern them, a rating chart for new equipment attributes, and inquiries as to the level of spending that occurs in each state on surface maintenance operations, specifically crack sealing. This information was combined with data from ERES as to the current level of practice in the various federal regions and how these practices might effect the utilization of automated crack sealing equipment. A copy of the Questionnaire is contained in Appendix ***TBD***, along with the tabulated results.

6.5 - Integrated Machine Cost Projection

This section will address the estimated cost of a commercial version of both the general (integrated) machine and the longitudinal machine. The cost of the prototype will be detailed here. This will be benchmarked against the issues received as feedback in those elements of the research marketing plan that have been executed, as well as being based upon the input we get from various manufacturing firms of large or heavy construction and roadwork equipment. An additional projection will be performed using standard cost projection models as practiced in the one-off design manufacturing market sector. These projections will take into account standard percentage projections for NRE and the subsequent cost of additional units produced.

In addition, an analysis and comparison will be made to existing heavy highway equipment that address one or more of the elements of crack recognition and\or repair. These systems will be used for cost comparison of "standard" highways equipment.

The cost of the prototype general machine is ***TBD**. This can be broken down into the following subsystem costs:

Truck Platform
ICU
VSS
LSS
VOC
RPS
APS
LRPS
Software Engineering for Integration & Control
Electrical Integration/Engineering
Mechanical Integration/Engineering
Manuals

From the above cost detail summary, the cost of the Longitudinal machine would appear to be ***TBD***. The true cost of the Longitudinal machine is ***TBD*** due to the cost of several support systems required to allow its' operation as a dedicated unit on a vehicle of opportunity or dedicated (smaller) maintenance vehicle. These additional system costs are:

APS
LSS
VIDEO SYSTEM
HPU
MELTER
MISC. SUPPORT EQUIPMENT
Electrical Integration/Engineering
Mechanical Integration/Engineering
MANUALS

6.5.1 - NRE Cost Model Analysis

NRE (Non Recurrent Engineering) cost analysis models were developed from an evaluation of several quotes for advanced system hardware development from a variety of market sectors. These included robotic equipment manufacturers, heavy industry (automated logging and forestry equipment) manufacturers, heavy roadway equipment manufacturers, and advanced recycling equipment vendors/manufacturers for the petroleum industries. In general it was found that NRE for the first unit produced accounted for approximately 45 - 65 percent of the quoted value/cost of the unit. Each subsequent unit cost approximately 35 - 55 percent of the first unit cost -- the difference being the NRE. These NRE activities/costs were typically associated with Electrical, Mechanical, and software engineering activities needed to make the new systems function within the given operating environments. These activities would be analogous to many of the current R&D functions being executed in the development of the current automated crack sealing equipment prototypes. In addition, it was found that fair market value was marked up by approximately 35 - 50 percent for manufacturers gross margin. This markup was consistent throughout the evaluated cases for equipment produced with a total expected market of less than 100 units. Within the traditional manufacturing sector where the market is estimated in thousands of units (or more) this type of markup is considered exorbitant and would typically be in the 5 - 15 percent range. This being noted, it was felt that the previous markup values would be more representative of the potential market for this equipment within the US Transportation (Infrastructure Maintenance) industry.

With these values in mind, we then find that the cost projections for the general machine are: ***TBD***; and the cost projections for the longitudinal machine are: ***TBD***.

6.6 - Cost Benefit Analysis

A revised cost benefit analysis will be made. This analysis will discuss the existing projection and compare how this comparison tracks with new information as a result of the continuing research work. Additional factors will be considered that reflect the feedback from other state DOT agencies and their perception of the vehicle system and its potential for use within their operations (a preliminary evaluation of the potential market). In addition, an analysis and comparison will be made to existing heavy highway equipment that address one or more of the elements of crack recognition and\or repair. These systems will be used for cost comparison of "standard" highways equipment.

The projected NRE cost model based values would appear to be, on a preliminary basis, consistent with earlier reported analysis (ref. "COST SAVINGS ANALYSIS OF NEW CRACK SEALING SYSTEM", reported in the Interim Report), and therefore could be anticipated to be a good value, excellent investment, and sound technology to be pursued in trying to meet the increasing demands on the State DOTs for maintenance and refurbishment of the highway systems in this country. However, in an effort to provide a comparison with other emerging technologies (which could be construed to be competitors to this method), a common means of evaluation was developed - the cost per lane mile. This cost model will allow comparison of this approach to roadway remediation and maintenance to other forms of the same, as thy are often bid on a square yard/meter basis which is translated into cost per lane mile.

The cost per lane mile is calculated to be:***TBD*** for the general machine and ***TBD*** for the longitudinal machine. In comparison, the cost per lane mile for conventional manual crack sealing is ***TBD*** and the cost per lane mile for HIP Recycling is ***TBD***. From this we can see that ....

6.7 - Suggested Modifications for Commercial Machine

6.7.1 - Introduction

There are two major issues that must be addressed as the prototype equipment evolves into a working, marketable product. The existing prototype is being developed with capabilities somewhat short of those which would be desired in transverse crack sealing equipment. For example, the final prototype will only seal transverse cracks within an 8-ft (2.4 m) wide swath, while ideally it is desired to be able to seal cracks a full lane width. Also, the prototype and its components are currently being developed to address transverse and longitudinal cracks in AC. A complete sealing machine needs to address several other types of cracks and joints.

This section identifies operations for which the automated sealing equipment could be adapted. Also included are discussions of the preparation methods and materials that are currently required for completing these operations, as well as a summary of the additional equipment that would be required. Not covered in this section are the additional modifications that are required to move the prototype equipment to a fully functioning, marketable product.

6.7.2 - Additional System Applications

The technology developed in producing the prototype crack identification and sealing machine can be applied to other types of sealing projects, resulting in faster, safer, and more consistent sealing operations. Among the sealing operations for which the automated sealing machine could be modified are the sealing of the following:

- Transverse contraction joints in PCC pavements.
- Longitudinal joints in PCC pavements.
- Longitudinal PCC/AC shoulder joints.
- Transverse cracks in PCC pavements.
- Longitudinal cracks in PCC pavements.

Each of these operations has a slightly different set of recommended preparations and procedures that require the modification of the current design or the development of new system components.

With the possible exception of transverse cracks in PCC pavements, each of these cases is a simpler test of the system's vision sensing capability and the algorithms that are currently used to identify sealable cracks and joints. This is true because transverse joints occur at regular intervals. They are either uniformly spaced or follow a repeated pattern (e.g., 12-13-17-16 ft) and are oriented either perpendicular to or at an 80 degree angle to the pavement edge. Longitudinal joints (either lane-lane or lane-shoulder) present even less difficulty in locating the joint position. Once the longitudinal or transverse joints are located, it will be fairly simple for the local sensing system to follow the joints for the preparation and sealing steps, since these joints are relatively straight and continuous.

6.7.3 - Transverse Contraction Joints in PCC Pavements

Transverse contraction joints in PCC pavements are located in the traffic lanes and PCC shoulders. Their purpose is to allow for shrinkage contraction and slight expansion of the concrete without compromising structural integrity. Movement of these joints is typically horizontal and can be quite large. In new construction, transverse joints are typically formed by sawing a 3/8 to 1/2-in (9.5 to 13 mm) wide by about 1.5 in (38 mm) deep channel in the cured concrete. These joints are typically spaced at a distance between 15 ft (4.9 m) and 60 ft (19.7 m) and are positioned either perpendicular to the lane edge or slightly skewed (usually 1:6) from perpendicular. The recommended practice for resealing these joints includes:

1. Removing the old sealant from the joint reservoir.
2. Sawing about 1/16 in (1.6 mm) from both faces of the reservoir.
3. Removing all wet-sawing slurry from the reservoir and allowing the reservoir to dry.
4. Sandblasting each side of the reservoir.
5. Airblasting the sand, dust, and dirt from the reservoir and surrounding pavement.
6. Inserting properly-sized backer rod or backer tape into the reservoir.
7. Installing the sealant material in the joint over the backer rod.
8. Tooling the surface of the sealant as required to achieve good adhesion.

Removing the sealant with a plow blade is necessary if the sealant "gums-up" a concrete saw blade. Sawing the joint faces is usually accomplished with a water-cooled, diamond-bladed concrete saw. The sawing operation leaves a slurry of cement dust, old sealant, and water in the joint reservoir. If the slurry is allowed to dry in the joint, it is very difficult to remove. Sawing residue is typically removed by water washing and airblasting the reservoir. After the plowing, sawing, and slurry removal operations are completed, the concrete is allowed to dry, typically for more than 24 hours. Then the sandblasting, airblasting, backer rod insertion, and sealant installation operations are completed in as rapid succession as possible.

The sandblaster must clean each joint face, and the sand and dust must be completely removed by airblasting and/or vacuuming. Spalling and variations in joint width can precipitate the need for using different sizes of backer rod, since the rod must fit tightly to the reservoir walls and to all adjacent backer rod. Recently developed "soft-type" backer rod is more forgiving of joint width variations, and may be used with cold-applied sealants. Backer tape has also been used, although its effectiveness has not yet been established.

6.7.4 - Longitudinal Joints in PCC Pavements

Longitudinal joints in PCC pavements are located at either the lane-lane or the lane-shoulder interface of full-width concrete pavements. In new construction they are typically sawed 0.25 to 0.5 in (6.4 to 13 mm) wide and about 1 in (25 mm) deep. Movement at these joints is generally small, especially if the joints are tied. The same methods listed above for preparing transverse joints are recommended for resealing longitudinal joints in PCC pavements.

6.7.5 - Longitudinal PCC/AC Shoulder Joints

Asphalt concrete shoulders are frequently used in conjunction with concrete traffic lanes. The longitudinal joint between the shoulder and the traffic lane should be sealed. Movement in these joints is typically vertical and can be large, particularly when the underlying soils are frost susceptible. There can also be horizontal movement due to separation. In most projects, the following methods are used to seal these shoulder joints.

1. Use an impact router or a dry saw to cut a reservoir in the asphalt concrete next to the concrete to a width of at least 1/2 in (13 mm) and the desired depth. A typical reservoir is 1 by 1 in (25 by 25 mm).
2. Sandblast the face of the concrete.
3. Airblast the reservoir and surrounding areas to remove all debris.
4. Insert backer rod into the reservoir to the proper depth.
5. Install the sealant in the reservoir over the backer rod.
6. Tool or screed the sealant surface as required.

In many cases, the AC shoulder surface is either above or below the concrete pavement surface. To keep the sealant at the proper level, the sawing and sealing equipment must adjust the cutting and sealant surface depth to the level of the lower AC or PCC surface. Failure to make this adjustment could result in an improper shape factor or an overfilled joint.

6.7.6 - Transverse Cracks in PCC Pavements

Transverse cracks in PCC pavements typically meander across a pavement perpendicular to the lane edge and range in width from less than 1/16 in (1.6 mm) to more than 1 in (25 mm). They can be "working" or "nonworking" cracks, and appropriate load transfer restoration or replacement options should be considered if the cracks are "working" cracks. It is suggested that cracks between 0.125 in (3 mm) and 0.75 in (19 mm) wide be sealed.[5] The recommended method for sealing these cracks include the following steps.

1. Use a small-diameter diamond-bladed saw or a vertical spindle router to create a 0.375- to 0.5-in wide and __ in (___mm) deep reservoir above the crack.
2. Sandblast the walls of the reservoir.
3. Airblast the reservoir and the surrounding pavement.
4. Insert backer rod into the reservoir to the proper depth.
5. Install the chosen sealant material, tooling as required.

[NOTE: items left blank in previous list to be determined for final report.]

Steps 2 through 4 must be completed in rapid succession to achieve optimum seal performance. Saws with small diameter diamond blades cut faster than vertical spindle routers, but they are not as maneuverable. Vertical spindle routers can be used to follow irregular cracks more easily, but they are slow and have a tendency to spall the concrete edges. Rotary impact routers will spall or crack the joint edges and should not be used.

6.7.7 - Longitudinal Cracks in PCC Pavements

Longitudinal cracks in PCC pavements are typically the result of ineffective methods of forming the longitudinal joint, improper longitudinal sawing, or poor pavement support. The method recommended for sealing these cracks is the same as that described above for transverse cracks. In some cases, these cracks divide in a "Y" pattern, forcing the automated equipment operator to make two passes or to seal the adjacent crack by hand.

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[5] Rigid Pavement Design for Airports, Chapter 7 – Standard Practices for Sealing Joints and Cracks in Airfield Pavements," Air Force Manual 88-6, January 1983.

6.7.8 - Desired Additional Material Handling

For automated resealing equipment to be useful in this extended set of applications, it must be able to install the sealant materials that have performed well and are currently in use. Current research indicates that some hot-applied, polymer-modified asphalt sealants are performing well in sealing cracks in AC pavements.[6] In addition, two other sealants are performing well for filling non-working longitudinal cracks in AC pavements.

- Polymer modified emulsion.
- Fiberized asphalt sealant.

The following materials are generally used for resealing joints and sealing cracks in concrete pavements.

- Nonself-leveling silicone.
- Self-leveling silicone.
- Certain polymer-modified, asphalt sealants (modified ASTM D-3405).

Hot-applied sealants (ASTM D 1190) are typically used for sealing the joint between PCC pavement and an AC shoulder. However, lower-modulus silicone sealants have recently been developed that may also perform well.

Preformed seals have been used to seal joints in new concrete pavement, but less success has been reported when resealing older joints. Performance is especially reduced when the joint edges are spalled and not perfectly smooth. Therefore, it is not believed that the use of automated sealing equipment to install preformed seals is appropriate or desirable at this time.

To meet the demands of resealing joints and cracks in AC and PCC pavements, the automated sealing equipment should be capable of installing polymerized emulsion sealants, fiberized asphalt sealants, and silicone sealants, in addition to its current ability to install hot-applied sealants. Since most sealant manufacturers recommend that sealant be recessed about 1/4 in (6.4 mm) below the pavement surface, the automated equipment must be able to accomplish this without spilling or wiping sealant on the adjacent pavement surface.

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[6] Evans, L. D., C. G. Mojab, A. J. Patel, D. G. Peshkin, A. R. Romine, K. L. Smith, T. P. Wilson, "Innovative Materials and Equipment for Pavement Surface Repairs – Initial Draft Report on Performance of Materials and Methods," Strategic Highway Research Program, SHRP-89-H-106, April 1992.

6.7.9 - Required Modifications and Component Development

Adapting the automated sealing machine to meet these additional applications and sealant materials requires that several additional pieces preparation, installation, and monitoring equipment be developed, installed, and tested.

6.7.10 - Accessory Joint or Crack Preparation Equipment

For preparation and cleaning of PCC joints or cracks, the following accessory equipment could be developed:

- Joint plow for removing old sealant from PCC joints.
- Diamond-bladed saw for refacing joint sidewalls in PCC.
- Waterwashing equipment and vacuum for removing sawing slurry.
- Vertical spindle router for widening cracks in PCC.
- Small-diameter, diamond-bladed saw for widening cracks in PCC.
- Sandblast apparatus for cleaning joint sidewalls.
- Vacuum for removing sand and debris.
- Airblasting equipment for cleaning joints and cracks.

A joint plow attachment must be able to remove enough sealant from the joint so that the sealant does not "gum-up" the concrete saw blades. The plow must not spall or crack the adjacent joint edges. Bits for the plow must be straight sided, not tapered. The best cleaning is accomplished by forcing the side of the blade against one side of the joint to literally scrape off the old sealant and debris. The process is then repeated for the other side of the joint.

A diamond-bladed saw attachment must follow the joint reservoir very closely, removing only 1/16 in (1.6 mm) from each sidewall. To maintain the position of the blade in the center of the joint, a centering guide is very useful. It is much easier to achieve consistency in joint width when "ganged" or full-width saw blades are used. Sawing is generally completed using a downward cut on the leading edge of the saw blade. More potential for cracking and spalling of the joint edge arises when the leading saw edge is cutting upward.

Waterwashing and/or airblasting should immediately follow the sawing operation. This attachment must be able to remove the sawing slurry from the joint reservoir, and should be accompanied by a vacuum attachment that removes the slurry and debris from the reservoir and pavement surface.

For creating a sealant reservoir above cracks in concrete pavement, a vertical spindle router or a small-diameter, diamond-bladed sawing attachment is required. Both attachments must be able to follow the cracks closely, developing a reservoir without cracking or spalling the joint walls.

A sandblasting attachment is necessary to remove the remaining slurry dust and small amounts of sealant from the joint sidewalls. The attachment must direct a stream of air and sand at each individual joint face, exposing clean, fresh concrete surfaces on both sidewalls to which the sealant can bond well. An effective vacuum attachment must be used in conjunction with the sandblasting operation.

To remove any remaining sand, dust, and dirt from the joint reservoir, an airblasting attachment may be necessary. The stream of air should be directed in such a way that it does not recontaminate previously cleaned joints.

6.7.11 - Accessory Sealant Installation Equipment

Immediately following joint or crack preparation, backer rod and sealant should be installed. Accessory installation attachments that must be developed to allow sealant installation in PCC joints and cracks include the following:

- Backer rod or backer tape insertion equipment.
- Applicator for installing silicone sealant and recessed hot-applied sealant.
- Tooling apparatus for nonsag silicone sealants.

Backer rod insertion equipment must be able to insert backer rod of various sizes into a joint to the design depth without tearing or stretching the rod. No gaps can remain between the rod and the sidewalls or at intersections of backer rod. Achieving a tight fit can be especially difficult when the joint edge contains spalls, and methods for addressing this problem must be developed.

A sealant applicator attachment must fill the joint from the bottom up, maintaining the sealant surface between 0.25 (6 mm)and 0.125 in (3 mm) below the pavement surface for most projects.

Good performance of the sealing equipment is extremely important to the long-term performance of a seal. In order to obtain the desired consistent surface level, the sealing equipment must be able to deliver a highly controllable amount of sealant. The sealing equipment should be able to install silicone sealants, emulsions, and fiberized asphalt sealants without over- or under-filling the joints or cracks. Nonself-leveling silicone sealants and fiberized asphalt sealants require different tooling operations to produce the desired profile. If these types of sealants are used, the sealant applicator must be able to form the sealant to the proper shape.

6.7.12 - Accessory Performance Monitoring Equipment

To ensure that the quality of preparation and installation is adequate, several accessory monitors may need to be developed.

- Depth sensing equipment for controlling router or saw height.
- System to monitor sandblaster operation.
- System to judge removal and cleaning effectiveness.

Feedback systems would also need to be developed to initiate the recleaning process as the monitors dictate. Commonly the surface of an AC shoulder is not level with the concrete pavement surface. If the depth of the sawcut and sealant surface level are controlled by the concrete pavement surface level, the sawcut may not form an adequate reservoir in the asphalt, and excess sealant may placed in the reservoir, spilling over onto the shoulder. The level of the saw blade and the installation attachment must be controlled by the height of the lowest pavement (AC shoulder or PCC pavement) so that a good sealant shape factor is maintained. This can be accomplished by using electronic depth sensing equipment or simply by using a foot or roller connected to the saw and sealant installation attachments that follows the lowest pavement surface.

It is sometimes difficult to maintain consistent sand and air flow from sandblasting equipment. If the sand is wet or the humidity is high, the moist sand can clog the nozzle. Likewise, if a small stone or other debris enters the blasting line, the nozzle can become clogged, and the sandblaster becomes ineffective. To prevent this situation from happening, the sandblasting attachment should be monitored for sand and air flow, and a feedback system should notify the operator of any problem.

The effectiveness of the cleaning equipment has a large impact on the performance of a joint seal, making it essential that the results of the sawing, sandblasting, and airblasting operations be satisfactory. An inspector is present at most major resealing projects to ensure that proper cleaning and installation results are achieved. To maintain high seal quality, the automated sealing equipment must have a method of ensuring that each apparatus is performing adequately. These sensors may be visual or based on other criteria, and an accompanying feedback network should be developed to initiate repetition of the process of a deficiency is noted.

6.8 - Additional Information

This section will be also include a summary of the recommendations of the researchers, any feedback from potential commercial fabrication companies, and an analysis from the viewpoint of continued standardization by integration of new/existing components that exist within standard inventories of heavy equipment manufacturers.

6.9 - Future Issues

This section will relate programmatic recommendations that relate specifically to the integrated machine, and the separated units (general machine and longitudinal machine) and commercialization. Additional Pre-commercialization research and prototype fabrication will also be addressed.

7

Maintenance Program With Automated Machinery

7.1 - Introduction

The integration of the automated sealing system into a highway agency's maintenance program is a multi-step process. The agency must first identify a need for the maintenance that the system performs. Decision criteria are then outlined to determine if the system meets the agency's needs. If the system does meet the agency's decision criteria, the equipment will most likely be tested in a contracted project. Then, if the system performs well and its cost-effectiveness can be demonstrated, the agency may regularly contract for the use of the equipment and its operator. The agency may also decide to pursue the possibility of joint ownership of the system with other agencies in its region. Finally, a fully- or partially-equipped system may be purchased, with the option to add capabilities at a later date. Each of these steps in the integration process are detailed in the following sections.

7.2 - Decision criteria

There are two fundamental decisions that need to be made as part of the automated equipment implementation process. The first decision is whether or not to acquire and/or use such equipment at all. Many agencies have rigorous procedures for procuring equipment and competing for available funding. This has a direct impact on decisions to acquire new equipment, because when budgets are cut, equipment purchases often have the lowest priority. Therefore, it is critical that the benefits and cost-effectiveness of the new equipment be clearly determined at the beginning of the procurement process.

The decision criteria used by a highway agency must be clearly defined before the potential for integration of a system into its maintenance program can be determined. Some important decision criteria include:

- The maintenance operation that the equipment performs must improve pavement performance enough to justify the expenditure for the equipment.
- The equipment must be durable, so that down-time and maintenance expenses are minimized.
- The technical difficulty and cost of repairs to the equipment must be manageable, as it is desirable to perform most repairs in-house.
- The speed and quality of work must be superior, especially when compared to already existent, satisfactory methods.
- Traffic control must be acceptable and user delays within a tolerable range.
- The equipment must be professionally manufactured, aesthetically built, and have proven performance.

If the equipment satisfies these criteria, highway agencies are likely to be willing to expend funding to integrate the system into their maintenance programs.

The second decision follows once an agency has determined that it is worthwhile to acquire the automated sealing equipment. That decision is, given access to, or even ownership of, the equipment, on what types of projects should it be used? The simple answer is that automated sealing equipment should be used on projects on which its use is cost-effective. If it is assumed that once the pavement is sealed, the repair placed by manual methods will last as long as that placed by automated methods, then it is only necessary to consider the actual installation costs in performing this analysis of cost-effectiveness.

Some of the costs associated with sealing operations are easily measurable. These include equipment costs, labor costs for the number of people required, and material costs, if the rate of use is different. However, two of the largest costs, user costs and safety costs, are not easily quantifiable. The use of an automated sealing system will reduce the direct exposure of highway workers to traffic. It will also reduce the exposure of traffic to both visual and physical disruptions in the roadway. As the operation approaches the speeds that are targeted for the final working equipment, it will also reduce lane occupancy time. Taken together, these will have a direct and positive, albeit non-quantifiable, effect on costs that must be considered.

Perhaps there exists a third decision that in some cases takes precedence over the normal decision-making process. The original objectives of SHRP in the automated maintenance equipment project area were to create new equipment system prototypes to:

- allow surface repairs or crack filling operations from a position off the roadway.
- reduce personnel requirements

must also consider maintenance operations associated with both high and low-volume traffic streams and urban and rural pavement networks.(REF SHRP RESEARCH PLANS, FINAL REPORT, MAY 1986).

These requirements suggest that even over 5 years ago, there existed agencies for which the decision to adopt the use of automated equipment was driven by factors that are not readily quantifiable, including user costs and safety costs. It is those agencies that will approach the use of automated equipment in a different manner from the majority of agencies that perform sealing. Where these other costs are valid concerns, it is likely that there will be strong incentives to use automated sealing equipment even when such use can not be supported by a strict cost-benefit analysis.

7.3 - Integration

Because of its high cost, it is unlikely that individual agencies primarily responsible for low-volume and rural pavement networks would be able to purchase this system. Nor is it likely that their needs would lead them to be interested in an automated system. Rather, interested agencies are likely to be those responsible for high-volume roadways in an urban environment. For such agencies, integration of automated sealing technology into a maintenance program would likely be accomplished in one of two ways:

1. Several highway agencies may share ownership of the equipment.
2. The highway agency may contract for use of the equipment and its operator.

7.3.1 - Shared Ownership

If the equipment is shared among highway agencies within a given state or region, the agencies' own crews will have to use and maintain the equipment. The agencies will have to develop a training program to provide the crews with the high level of technical training necessary to operate and maintain the equipment.

7.3.2 - Contracting for the Service

It is more likely, however, that the majority of equipment use will be from maintenance contracting. In this case, two types of contracts may be used: 1) a contract for final hourly cost for use of the equipment with a specified minimum number of hours to be used on each contract period, or 2) the highway agency may take bids for work on a specific project. In order to make the use of the equipment cost-effective, contracts should provide for a long-term commitment (2 years or more, if possible under the agency's contract laws).

7.4 - Gradual integration

The most likely initial use of this machine by highway agency maintenance crews is for longitudinal crack sealing. This is an application for which the technology is already competitive with existing alternatives. The modules that perform this function are well advanced in their development, and their cost is comparatively low. There are several applications in which longitudinal crack sealing is the predominant activity, and this equipment could be used to address that need immediately. These cases include reflective cracking of a lane-shoulder joint on an AC widening project, some longitudinal joint reflective cracking, and cold joints on AC paving projects.

Later, the transverse crack sealing equipment could be integrated, as its capabilities develop from a prototype to a fully functioning version. Even at this stage, it is envisioned that a gradual integration of the machine would be desirable. For example, there are several components that individually carry out specific tasks in crack sealing program. These include the router, the heat lance, the vacuum, and the sealant applicator. Since not all agencies use all of these components in their crack sealing programs, an appropriate gradual integration might include the use of the applicator only, followed by the router and the applicator, the router, and then the full system. It is also suggested that appropriate tests of the system on actual highways would actually start with the easiest application, on low volume roads, and then later be introduced in more demanding applications.

Highway agencies will probably test the usefulness and cost-effectiveness of the equipment through contracted projects before considering purchasing the equipment themselves. If several agencies decide to share ownership of the equipment, it is likely that the equipment would initially be purchased with the crack sealing and filling features. It is highly probable that highway agencies would continue to contract for joint resealing. However, agencies that share ownership of this equipment, initially rigged for crack sealing and filling, may add joint resealing capabilities to the equipment at a later time.

8

Conclusions and Recommendations

9

Glossary

10

References