PROJECT REPORT

DESIGN AND INSTALLATION OF A

Tele-operated and Automated Maintenance Equipment Robotics (TAMER) System

Installed On a CASE 721B Front End Loader
Rev 1 (December 4, 1998)

Prepared for:

UNIVERSITY OF CALIFORNIA, DAVIS

Prepared by:

UCD-ARR-98-12-04-01

Unmanned Solutions, Inc.

940 Auburn Court
Fremont, California 94538
TOLL FREE: 1-(800) 241-2310
Fax: (510) 656-7480
Email: usi@unmanned.com

Unmanned solutions Inc.

Contents:

1.0 Background Information

The California Department of Transportation (CalTrans) has determined that there is a need for some form of remote control system for the front-end loaders their workers use to clear landslides and avalanches. Ideally, such a remote control system would allow the worker to clear an unstable or hazardous road blockage from a distance of 300 to 500 feet away - far enough away that the operator is not at risk of injury or death. CalTrans has worked with the University of California at Davis (UC Davis) to research and develop a prototype radio controlled front-end loader (referred to as the Tele-operated and Automated Maintenance Equipment Robotics project, or TAMER project) to demonstrate the feasibility of the concept. In a technology transfer contract with UC Davis, Unmanned Solutions, Inc. (USI) has undertaken the development of a commercial grade **TAMER** system and has installed this system on two CalTrans owned Case 721B Front-End Loaders. The first system was delivered to CalTrans District #1 in February 1998. The second system was delivered to CalTrans District #5 in August 1998. This report describes the process of development for the commercial **TAMER** system.

2.0 Project Description

2.1 USI TAMER Design

The project consists of three major elements - the loader itself, a "backpack" mounted remote operator control unit, and a "sit-down" simulated cab remote operator control unit (Figure 1). Communication between the loader and the control units is via a spread-spectrum radio modem operating in the 900-928 MHz frequency band. Only one controller at a time is able to deliver control commands to the loader. The control units transmit data used to provide analog control movement of the loader arm, bucket, clamshell, steering, throttle and brake. There are also digital signals transmitted for starting and stopping the engine, choosing gears, choosing direction of travel, operating the horn, Emergency Machine Shutdown/Stop, and four automatic 'detent' signals for leveling the bucket, raising or lowering the arm, or "floating" the arm on the ground.

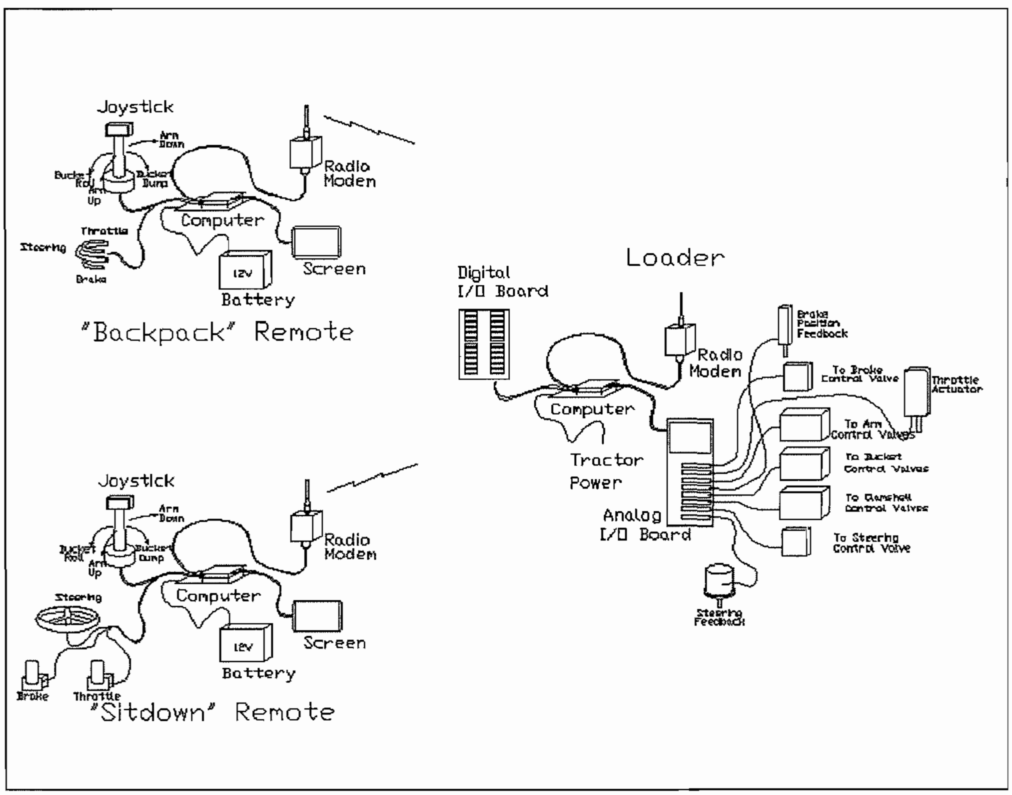


Figure 1 Front-end Loader Remote Control System

Modification of the loader for remote operation consists of installing industrial grade digital and analog I/O and a control computer in the cab behind the operators' seat, and several hydraulic valves underneath the cab. The remote control system hydraulic valves are piped in parallel with the loaders' normal control hydraulics and do not interfere with the use of the loader as a normal, manually operated loader. As a design decision and safety consideration, USI chose not to parallel the hydraulic system used to control the loaders' brakes. We instead chose to actuate the brake pedal in the cab using a small hydraulic cylinder with a proportion pressure control valve and a linear feedback device. The equipment manufacturers' original brake system remains intact and operable manually when in local or remote control mode.

The remote operator control units are designed to be interchangeable. The system electronics for each remote control unit are enclosed in a watertight aluminum suitcase with a 50-conductor umbilicus that connects to either the backpack or sit-down units' control interface. The remote control units are powered by an internal rechargeable battery, but may also be run from an external DC power source such as a truck battery. Connectors on the suitcase exterior provide attachment for battery recharging or external power operation. A switch on the suitcase determines whether the unit is recharging or operating from an internal or external power source.

Every piece of equipment used is able to withstand exposure to or enclosed to protect it from physical damage, rain, snow, cold, dust, heat and sunlight.

2.2 Comparison to Original Work done by UC Davis

The contract for developing a commercial TAMER system and installing it on two CalTrans owned Case 721B Front End Loaders stipulated that certain improvements and features beyond the UC Davis design were to be incorporated. Additionally, differences between the physical systems on the Case 621 loader modified by UC Davis and the Case 721 series loaders to be modified by USI dictated a slightly different approach to the control system design.

Most of the control devices on the UC Davis TAMER are "digital" – the functions are implemented by turning solenoid control valves on or off. This means that any positioning of the boom-arm, the bucket, or steering is at a single set speed. Problems sometimes arise from this fact, especially in steering the loader, as the ability to make fine adjustments to position or direction of travel depends entirely on the ability of the operator to "bump" the loader to the desired location or direction. "Jerky-ness" seems to be a common complaint. Most motions are made at a single, preset speed. The USI installed TAMER system consists of mainly proportional hydraulic pilot valves that parallel the existing tractor manual controls. The proportional valves allow a degree of speed control to nearly all of the tractors' functionality. The boom-arm and bucket can be positioned with variable speed, as can the direction of travel. Steering in the USI system is controlled by a software servo loop that uses information from the remote control unit and feedback from a rotary encoder mounted on the tractors' articulating joint to quickly set the tractor moving in the direction that the operator desires.

Braking for the original TAMER is accomplished using three different valves, the valve or valves being opened depending on the rate of braking desired. Additionally, the UC Davis brake system is an "air over pneumatic" system, and required the installation of solenoid operated valves in the tractors' hydraulic system both to implement the braking and to switch between remote and manual operation. The USI braking system design has left the existing brake system hydraulics undisturbed. We chose instead to operate the brakes using a proportionally controlled hydraulically operated pressure control valve that positions a small hydraulic cylinder to actuate the cab brake pedal linkage. The USI system includes a linear feedback device for improved brake control. The normal brake pedals remain undisturbed and functional at all times.

Throttle control on both the UC Davis system and the USI system is performed through use of an electro-mechanical positioner. A proportional voltage signal is sent to the positioner and it does the rest of the job. Both systems use yokes to actuate the throttle pedal in the tractors' cab yet allow a driver to override/use the same pedal for manual operation.

3.0 System Details

3.1 Loader Remote Control System

The control system installed on the loader consists of the following elements:

1. Single-board I486 computer
2. an eight-channel analog I/O board
3. a 24 position digital I/O board
4. five proportional control valve driver modules
5. two feedback potentiometers
6. a spread-spectrum radio modem
7. three DC/DC power converters to provide 5VDC, 12VDC and +/- 15VDC

The computer receives control commands via the radio modem, validates and interprets the messages received, and executes the received commands through the analog and digital I/O boards. Most commands received by the computer are directly executed (shutting off the engine, braking, steering, throttle, gearing and direction of motion, opening or closing of the clamshell, raising or lowering of the boom, and dumping or curling the bucket). Other commands trigger pre-programmed command sequences (Emergency Machine Shutoff, starting the loader, automatic bucket rattle, leveling the bucket, moving the boom arm to dump, travel or float positions). If the computer does not receive valid commands from a control unit within a preset time period, the computer applies the brakes itself, puts the loader into neutral, stops all motion of the boom, bucket, clamshell and steering. When this state is reached, the computer will wait six seconds for a remote control unit to re-establish communication, and shut the engine off if communication is not re-established. At this point the computer will hold the brakes on and wait for a remote control unit to establish contact with the loader again.

Operation of the boom arm, bucket and clamshell are achieved through proportional hydraulic control valves piped in parallel to the existing manually controlled hydraulic pilot valves. There is one pair of proportional valves for each function. Each valve pair shares one proportional valve driver unit, which receives a control signal from one channel of the analog I/O board. Selection of which valve of the pair is "active" (which direction the boom, bucket or clamshell will move) is made through selecting one of a pair of relays on the digital I/O board that correspond to the valve pair.

Steering of the loader is accomplished via a Proportional–Integral-Derivative (PID) control loop. The steering "setpoint" is obtained from the remote control unit, and is basically a numeric value ranging from 0.1 (full left turn) to 99.9 (full right turn) with a value of 50.0 corresponding to "straight ahead". This value and the feedback of actual loader articulation measured by a rotary potentiometer connected to the loaders' articulating joint are used to determine the control signal that is sent to another proportional valve driver unit. The output of this driver unit is switched by relays on the digital I/O board to one of two electric coils used to position the hydraulic steering valve that has been installed in parallel to the manual steering system. By setting the wheel or control bar of the remote control unit to the angle of articulation desired the loader articulates to that angle, providing steering of the loader.

Throttle control is accomplished through use of an electro-mechanical positioning unit that is linked to the gas pedal. A signal is sent to the actuator from the analog I/O board, and the actuator moves to a position corresponding to the value of the signal. All control and feedback is internal to the actuator.

Various relays on the digital I/O board fill in the other control functions such as starting or stopping the engine, gear and direction of travel selection, honking the horn etc.

The majority of electrical components are mounted in a control box inside the loader cab behind the drivers' seat. The control box is small enough that it does not obstruct the operators' view to the back or sides of the loader. Mounted atop the control box are a keyswitch and a red mushroom-head button. The keyswitch activates the remote control system (de-activating the ability to manually start the loader: all other manual controls remain active). The mushroom-head button allows someone in the cab to shut off the loader in the event that someone else starts it remotely before the operator can get out of the cab.

3.2 Brakes

The loader braking system deserves special consideration when discussing the design areas where we encountered significant difficulties. It was clear from the initial stages of the project that no one really wanted to modify the existing brake hydraulic system. Everyone's main concern was liability. Even the installation of a parallel set of piping was deemed risky. USI came to the conclusion that the best coarse of action was to somehow actuate the brake from a linkage to the foot pedal in the cab. Several methods of actuation were evaluated, and what seemed like a good fit for this application was chosen. The actuator chosen was a self contained electro-mechanical servo actuator with a 3 inch stroke, a speed of 3 inches per second, up to 90 pounds of force available, and requiring 12VDC power and a 1 to 3VDC control signal. An added bonus was that the same actuator could be used to press the throttle pedal.

These electro-mechanical actuators were installed in the first loader to ship. Initially, the actuator doing the braking seemed to work OK, but there was concern that the stopping distance was unacceptably long. As testing continued, the braking distance grew longer and longer. Several adjustments of position, linkage, and software took place before the unit shipped, yielding only modest improvements. Once in the field, CalTrans operators decided that the loader simply did not stop fast enough. We performed one more work-over of the braking system, and got a very good, fast application of the brake. Limited use on the part of CalTrans saw a rapid deterioration of brake operation.

At USI we came to the conclusion that an electro-mechanical unit would not be adequate for actuating the brake. Working with our hydraulic subcontractor we settled on a hydraulic cylinder to push the brake pedal down.

Loader braking is now controlled through a PID loop. The loop consists of a setpoint delivered from either the remote control unit OR, in the event of communication loss, the onboard computer, feedback from a linear potentiometer, and an analog signal from the analog I/O board that is sent to a proportional valve driver unit that is mounted directly on the control valve. The valve used for brake control is a proportional <u>pressure</u> control valve. The output of the valve is directed to a hydraulic cylinder that is linked to the brake pedal. This valve controls the amount of force applied to the brake pedal in the loader cab, while the linear potentiometer provides position feedback. The entire system is powered using the pilot lines of the tractor hydraulic system, and has an accumulator that stores sufficient energy to operate the brake system up to three times after the loss of system pressure. The tractor can nearly stop on a dime in an emergency shutdown mode, and otherwise acts similar to the manually controlled brakes, allowing slowing as well as coming to a complete stop.

3.3 Remote Operator Control Units

There are two configurations of Remote Control Unit; the Stationary Remote Operator Unit (SROU) or "sit-down" unit, and the Mobile Remote Operator Unit (MROU) or "backpack" unit. Each Remote Operator Unit consists of a control interface and a Control Suitcase.

3.3.1 Control Suitcase

The suitcases for both Remote Operator Units are identical and interchangeable. Each suitcase houses the following items:

1. Single-board I486 computer w/analog input board and LCD driver board
2. 24 point digital I/O board
3. Power-Mode switch
4. 12 Volt DC Battery
5. Undervoltage Relay
6. DC/DC Power converters for 5VDC and 12VDC
7. External connectors for battery recharging and external power source
8. 50-wire umbilicus to connect to either control interface

Once the suitcase is connected to the control interface the computer can begin monitoring analog and digital input data from the interface and begin sending control messages to the waiting loader. The control interfaces are different, so when switching a suitcase from one interface to the other, it is always a good idea to re-calibrate the analog input information. Once this has been done, the computer obtains analog signals from the interface, uses the calibration data to "normalize" the analog signal, and then sends the normalized control values to the loader.

3.3.2 SROU Interface

The "sit-down" unit partially mimics the loader cab. There is a seat from which the operator "drives" the loader. Steering is done with a "steering wheel" attached to a rotary potentiometer, brakes and throttle are floor pedals with their own built in potentiometers. Boom Arm and Bucket control is from a joystick on the operators' right-hand side that provides two analog voltage signals.

The "sit-down" unit begins to differ from the cab of the loader at this point. Forward/Neutral/Reverse are selected via a toggle switch mounted at the top of the Bucket/Boom joystick. Also mounted at the top of the joystick and actuated via toggle switches are the bucket clamshell Open/Close toggle, and toggles to activate the four "detent" or "pre-programmed" Bucket/Boom positioning functions (Bucket Level, Boom to Dump or Travel height, and Boom to Float). There is a trigger on the joystick that actuates another "pre-programmed" function – rattling the bucket. The choice of 1st or 2nd gear is a toggle switch on a box mounted on the SROU "dashboard". It is also from this box that the operator "Starts" and "Shuts-down" the loader, as well as performing a recalibration if a new suitcase has been installed in the SROU.

3.3.3 MROU Interface

The "backpack" unit consists of a backpack frame on which the control suitcase is mounted and a "chestpack" box on which all of the control devices are mounted. Steering is done with a "steering bar" attached to a rotary potentiometer mounted on the left-hand side of the box. Attached to this steering bar are a brake bar and a throttle bar, each with its' own potentiometer. The three bars swivel together (for a total range of motion of about 90 degrees) on a pin in a horizontal plane, and the steering value sent to the loader is derived from the rotation about the pin. The brake bar pulls up towards the steering bar to generate the brake signal, and the throttle bar pulls down to the steering bar to apply throttle. Bucket/Boom control signals are derived from a joystick mounted on the chestpack box. All of the toggle switches noted in the description of the SROU are in the same locations for the "backpack" unit. ". The same arrangements are made on this box for the operator to "Start" and "Shut-down" the loader, as well as perform a recalibration if a new suitcase has been placed on the backpack frame.

Unmanned solutions Inc.

FIGURE 2

FIGURE 3

Mobile Remote Operator Unit (MROU)

FIGURE 4

FIGURE 5

Stationary Remote Operator Unit (SROU)

3.4 Radio Control Linkage

Perhaps one of the most critical elements of this project is the actual radio based control linkage. When USI first undertook this project we chose a spread spectrum radio modem unit that had 21 channels (selectable via DIP switches) in the 902 to 928mHz range. This radio modem is capable of reliable communication at rates of up to 9600 baud. Its' outdoor range easily exceeded the 500ft operating range called for in the project specifications. We developed a communication message that provided for positive identification of sending and intended receiving stations, easily parsed command structures, and a simple message validation via a cyclic redundancy check character added to the end of a message.

Throughout our development efforts with the first loader communications between the loader and the remote control units seemed to work reliably. Even early testing with both of the loaders operating in the same area seemed to work fine, demonstrating no interference between the two systems. It was pretty late in the day, in an open field behind our facility, when we finally encountered a significant amount of interference that basically had the two loaders stopping and starting and stopping again. Even when the loaders were responding, the response was extremely sluggish. In investigating what was happening it was determined that there was so much radio noise in the area that the computers in the loaders were being overwhelmed with processing and rejecting what amounted to a great deal of garbage.

We decided to replace the radio modem in hopes of finding another style of unit that could reject most of the noise. A radio modem was found that communicates at 38400 baud, has its' own ID name, can be told the ID name of the radio modem at the other end of the link it is supposed to establish, and has its' own error detection/rejection. This new radio modem has proved quite successful so far. It takes a great deal of the communication processing load off of the loader computer as most of the local radio noise is rejected by the radio modem before the computer ever receives it. It is limited to four channels in the 900mHz range, but as each set of radio modems can be given unique ID names and told only to communicate with certain other named radio modems, this does not seem to be a limitation. Additionally, the power consumption of this new unit is significantly less than the first radio modem, allowing extended battery life in the remote operator units.

3.5 Safety System Description

Safety, of course, is the main reason for the existence of this project. It would therefore be unseemly for a TAMER equipped front-end loader to "run away" due to a computer or software failure. In our design we included several safeguards to prevent such an occurrence. On bootup, the software onboard the loader activates a watchdog timer built into the computer motherboard. This timer needs to be reset every 1.5 seconds or the software re-boots, resetting the loader control system to a non-running state, equivalent to an Emergency Shutdown command. In addition to the built-in computer watchdog timer, there is a watchdog module wired into the TAMER control packages' remote ignition circuit that must be reset every 2.0 seconds or less, or again an Emergency Shutdown event takes place. The commands that reset these two watchdog timers are located in different control loops of the TAMER software, insuring that even if the software gets stuck in the control loop that resets one of the timers, the other timer will shut off the loader.

Another protective measure we have taken involves monitoring the frequency and quality of the communication link between the loader and the remote control units. Once a communication link has been established between the loader and a remote control unit, the loader must continue to receive valid control messages from the remote unit on a regular and timely basis. The validity of a control message is verified by use of a 16-bit Cyclic Redundancy Checksum calculation. The result of the calculation is compared with the last two characters of the control message being verified. If the message is validated, the message is then parsed, interpreted, and executed. To continue operating, the loader MUST receive at least one valid message every 0.5 seconds. Should the loader not receive a valid message in the allotted time or receive six consecutive invalid messages, the loader shifts into neutral, applies the brakes, releases the throttle, and waits six seconds for valid communication with the remote control unit to re-establish. If communication is not re-established in six seconds, the loader automatically stops the engine, applies the brakes, and waits for a remote control unit to establish a new communication link.

As a final protective measure in this current design a secondary radio modem dedicated strictly to an Emergency Shutdown signal has been incorporated. The signal is generated by the control computer in the remote control unit, and sent to the loader via this secondary modem. In the loader, the receiving modem is connected to a separate monitoring computer whose only function is to initiate an Emergency Shutdown of the loader if such a command is received.

3.6 Evaluation of System

Factory testing was successfully performed at USI before any of the Skip Loaders were shipped to Districts 1 and 5. Final testing and training was performed at each district. Different terrain conditions were selected for testing. The response of the braking system was successfully tested on flat and inclined positions. Conditions of e-stop were also successfully tested to assure "brake holding". Steering performance was tested as well as all functions of shifting, bucket operations, and "shut down ".

4.0 Recommendations

There are many improvements that can be made to the USI TAMER design. The MROU unit in particular is quite heavy, and could be lightened significantly with what USI has learned from construction of the first two units. Also, since design work and construction of the remote control units was undertake there have been interesting developments in low power consumption devices that simply were not available to USI before. Ultimately, anything USI can do to cut down on remote control unit power consumption can reduce the weight of and extend the life of the batteries that power the units. Another potential weight saver would be selection of a different joystick for control of boom-arm/bucket functions.

On the loader potential improvements over the existing USI design are minor. A re-evaluation of hydraulic valve sizes/flow rates could provide modest performance improvements to most of the remotely controlled systems. The braking system could benefit from a lower flow rate pressure control valve, while the steering might benefit from a larger valve. Boom and bucket proportional control valves currently have similarly sized flow rates for both directions of operation, and could benefit from having lower flow rate valves in the "gravity driven" directions - lowering of the boom arm and dumping of the bucket – to make operation in those instances smoother and more controllable.

A significant improvement in battery life and weight for the remote control units could be achieved by elimination of the second radio-modem used for the backup Emergency Shutdown signal. The implementation of parallel watchdog timers, as well as the strict requirements imposed by the control communication scheme we have implemented make the backup Emergency Shutdown signal an unnecessary extra load both on the remote control unit batteries and the operators' backs. An additional argument involves the very reason for the existence of the project – the TAMER package is for remotely operating a loader under conditions where it is too hazardous for people to be present. With the two watchdog timers and the communication monitor functioning, the loader at absolute worst case will, on loss of control signals, stop in 0.5 seconds and wait for control to re-establish. If a catastrophic failure of the software occurs, the loader will at absolute worst case go into a complete Emergency Shutdown on its own in 1.5 seconds. A worst case analysis would be to postulate a catastrophic software failure (looping in the motherboard watchdog reset routine) at the same time that the operator is driving the tractor at full speed in second gear at someone or something. Assuming top speed in second gear is 25 MPH (faster than I believe the loader will go in second gear) the farthest it could travel before the second watchdog timer module initiated an Emergency Shutdown would be 73ft. By using a 0.5-second watchdog module instead of the two-second module currently installed, that worst case distance becomes 18.25ft. It is entirely conceivable that the operator will not even notice that control has been lost before the loader shuts itself off.

APPENDIX A

MECHANICAL DRAWINGS

Unmanned solutions Inc.

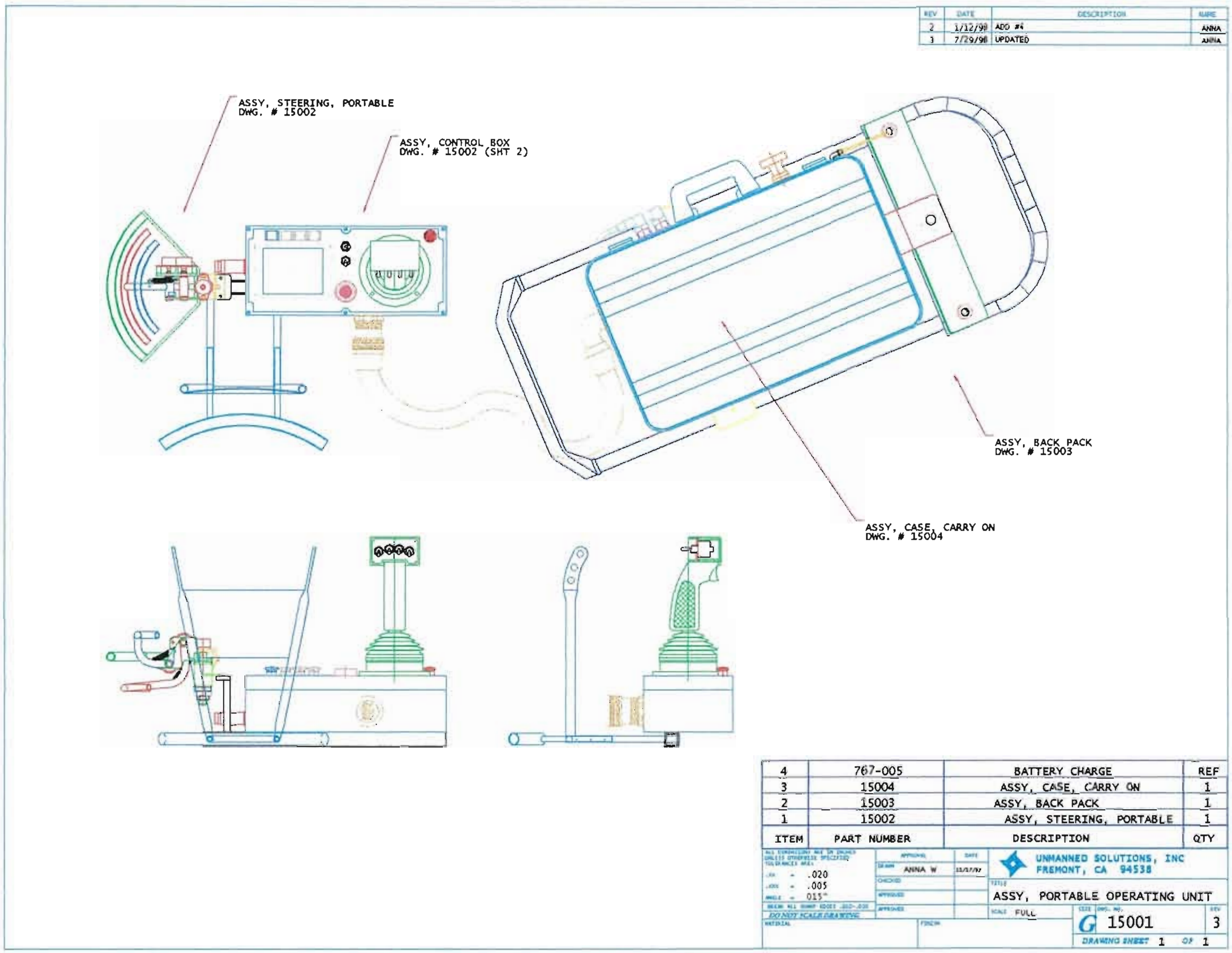


FIGURE A-1 PORTABLE OPERATING UNIT (PROU)

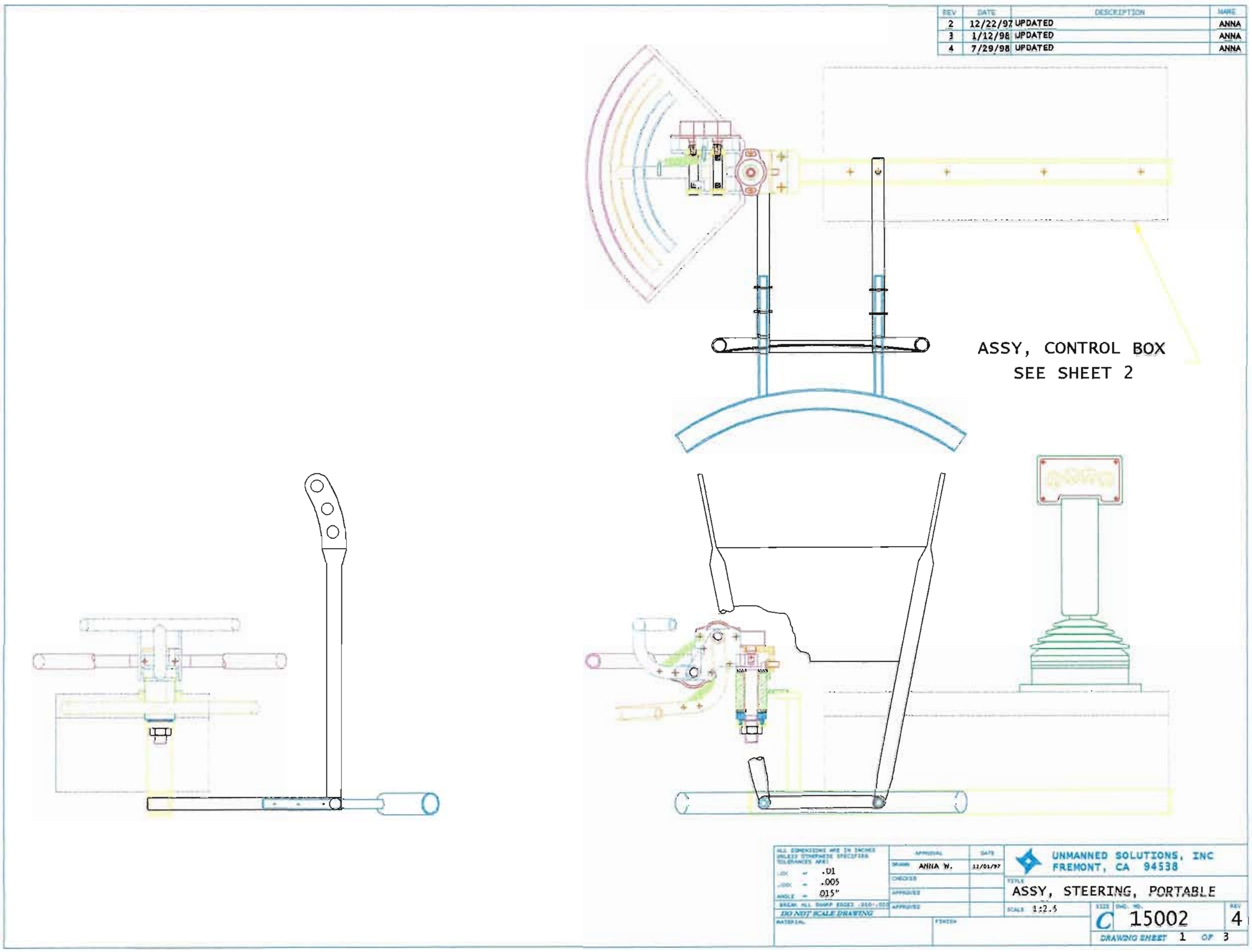


FIGURE A-2 STEERING ASSEMBLY

Unmanned solutions Inc.

<u>Unmanned solutions Inc.</u>

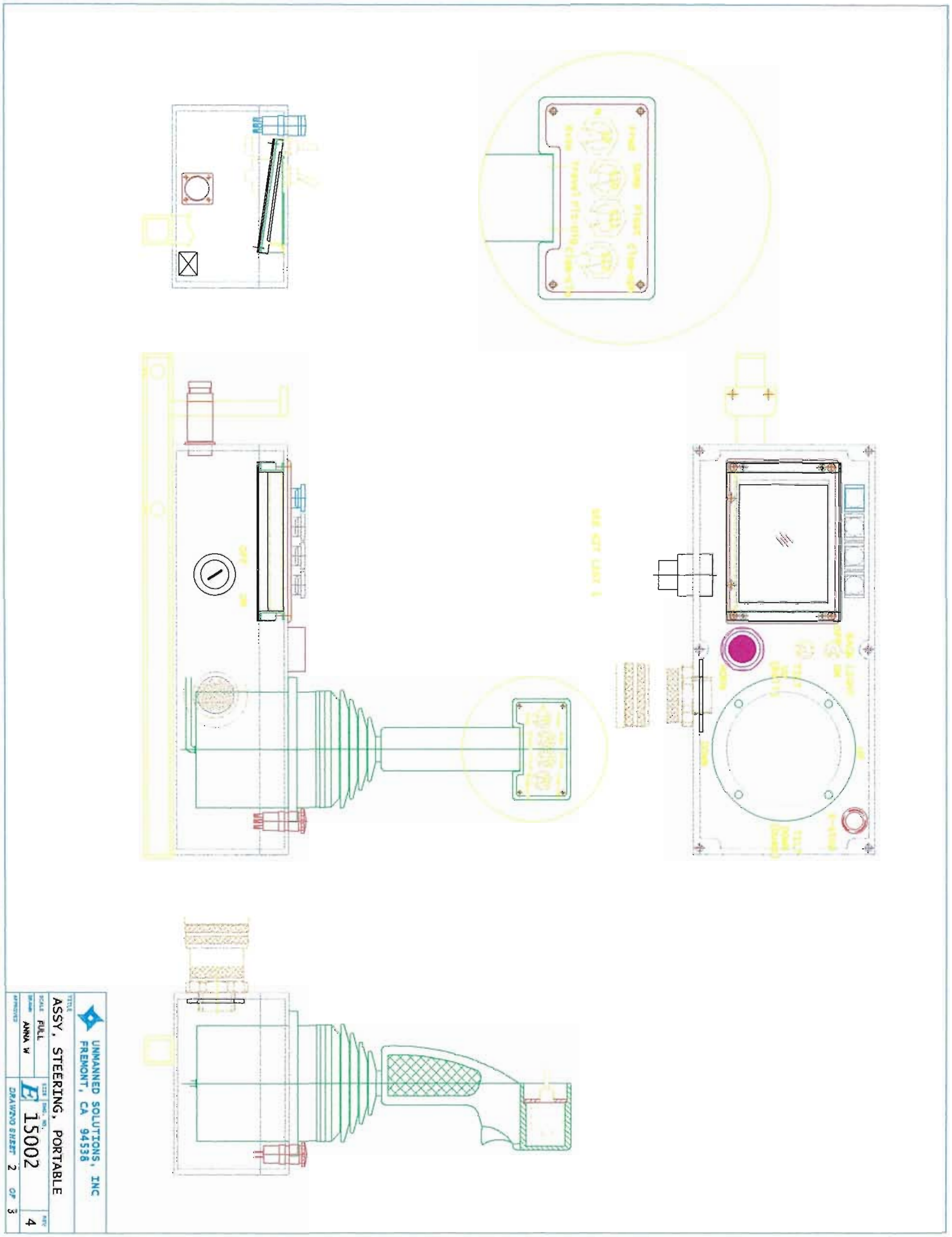


FIGURE A-3 PORTABLE STEERING (JOYSTICK)

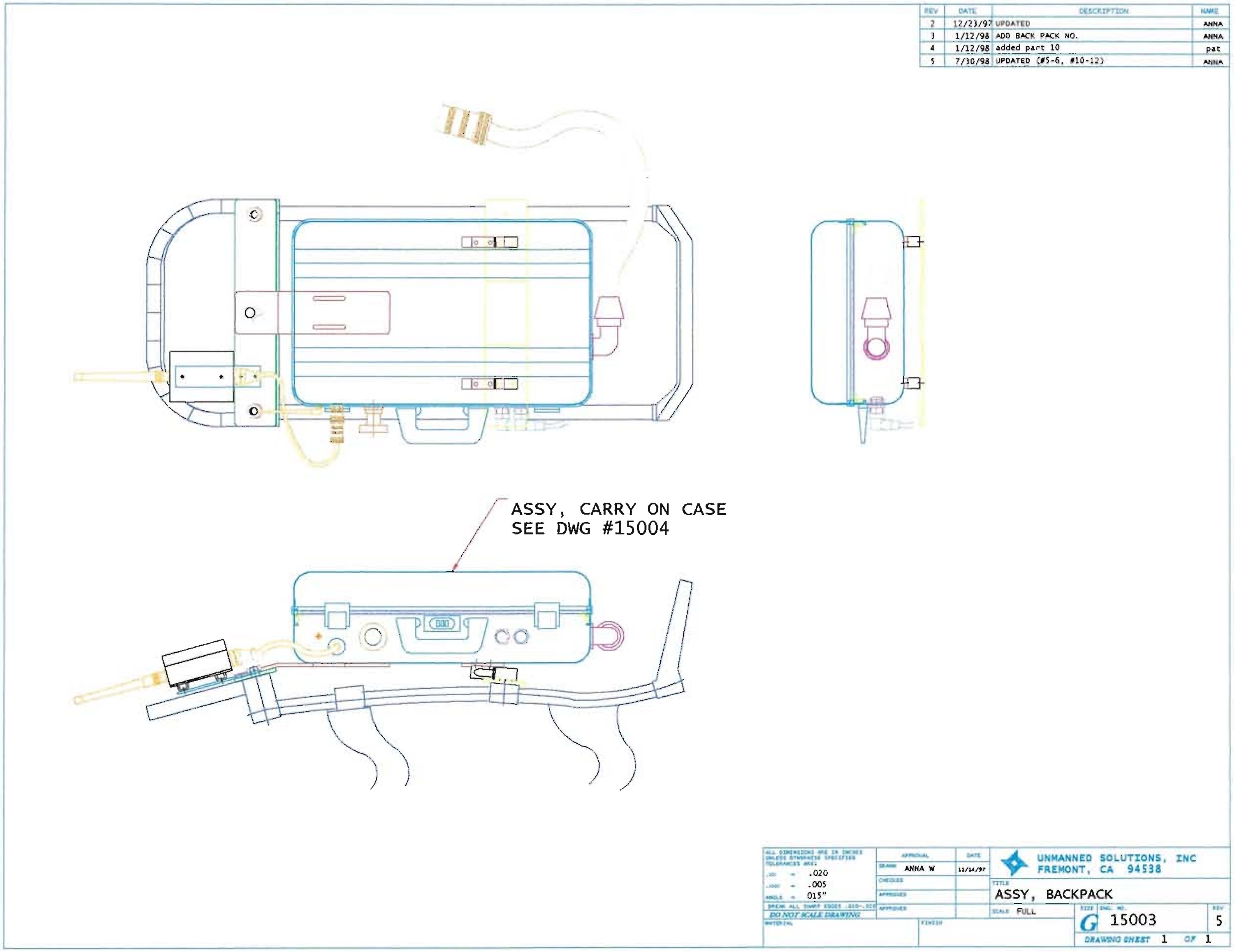
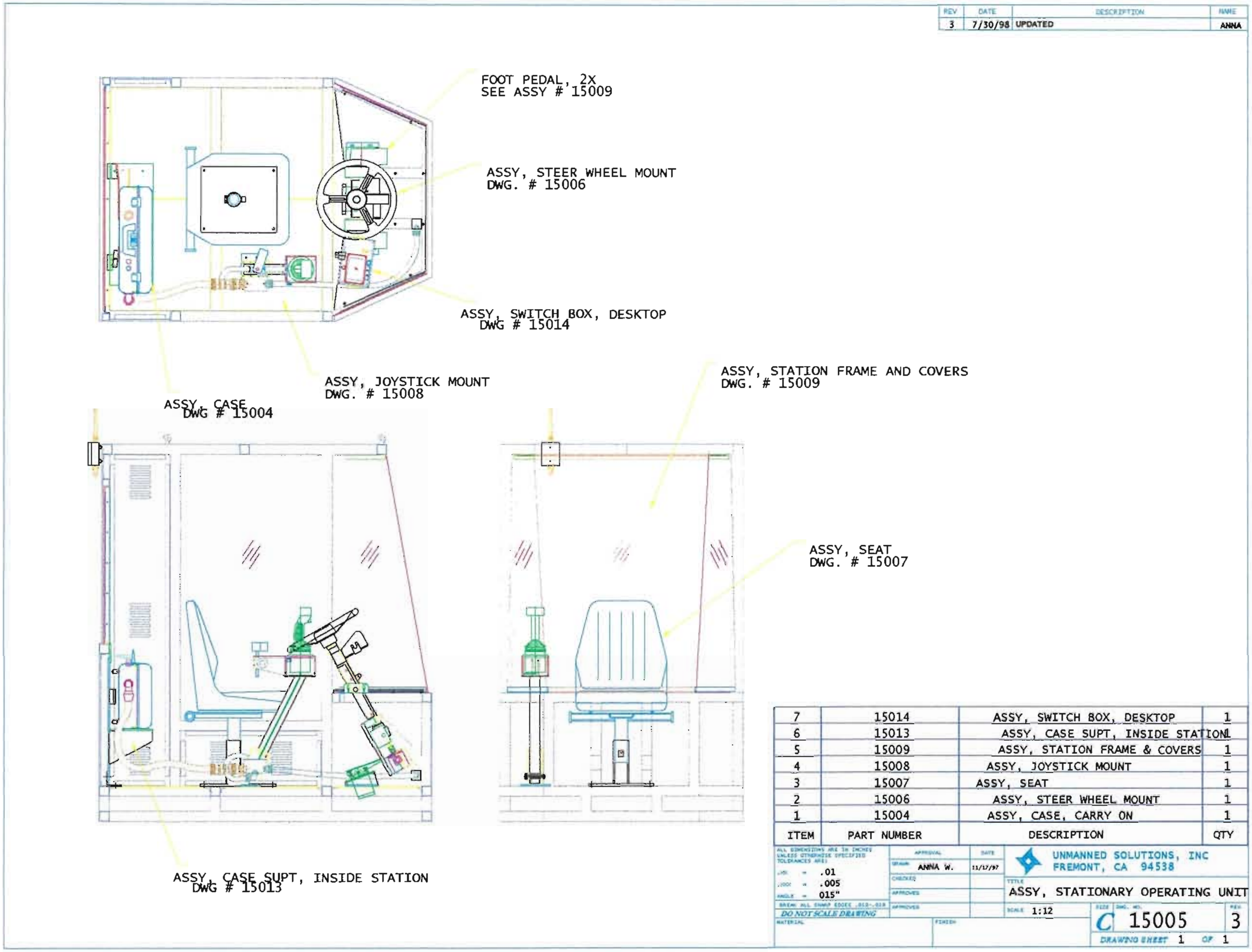


FIGURE A-4 BACKPACK



ITEM	PART NUMBER	DESCRIPTION	QTY
7	15014	ASSY, SWITCH BOX, DESKTOP	1
6	15013	ASSY, CASE SUPT, INSIDE STATION	1
5	15009	ASSY, STATION FRAME & COVERS	1
4	15008	ASSY, JOYSTICK MOUNT	1
3	15007	ASSY, SEAT	1
2	15006	ASSY, STEER WHEEL MOUNT	1
1	15004	ASSY, CASE, CARRY ON	1

FIGURE A-5 (SROU) STATIONARY REMOTE OPERATING UNIT

Unmanned solutions Inc.

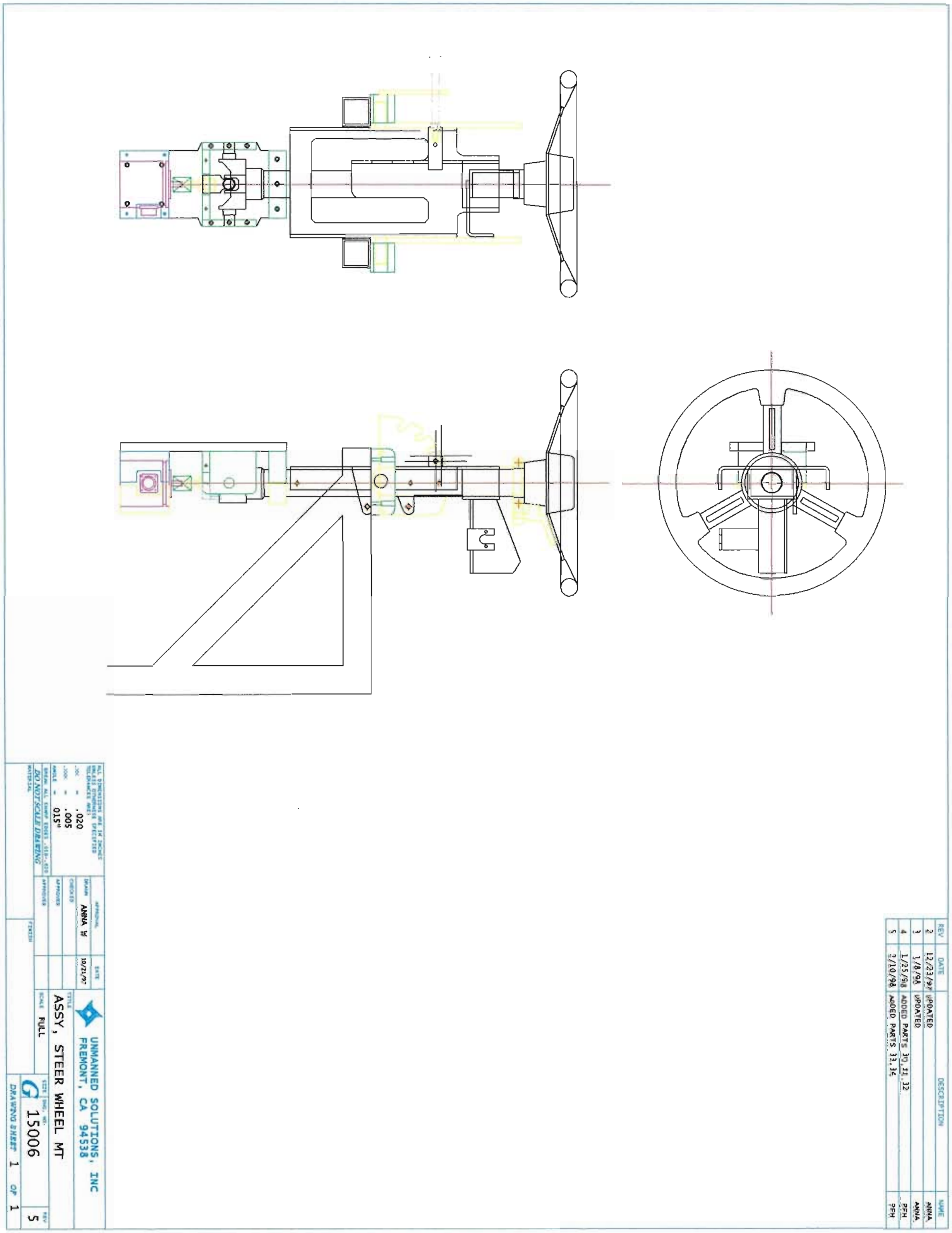


FIGURE A-6 STEERING ASSEMBLY FOR THE SROU UNIT

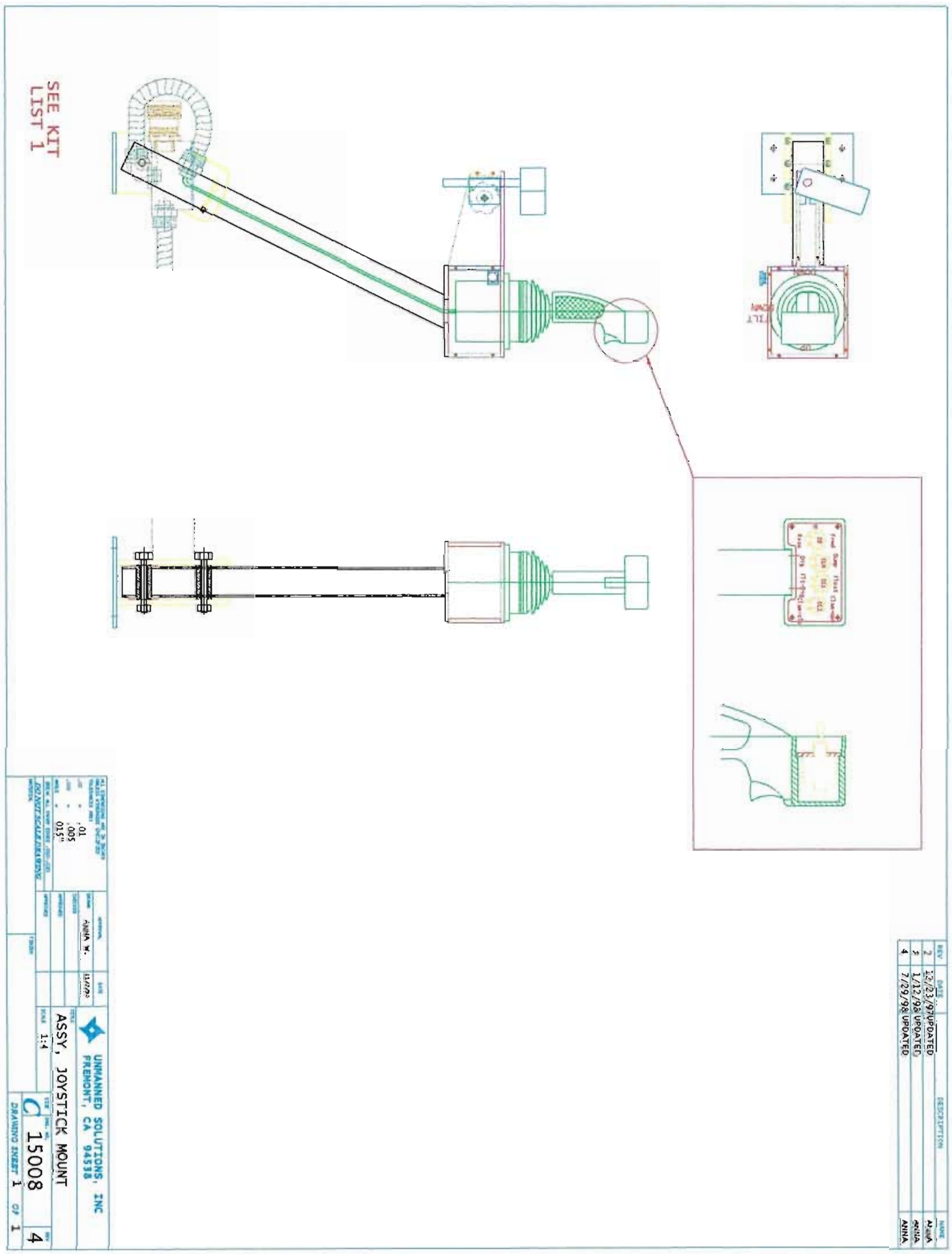


FIGURE A-7 SROU JOYSTICK ASSEMBLY

Unmanned solutions Inc.

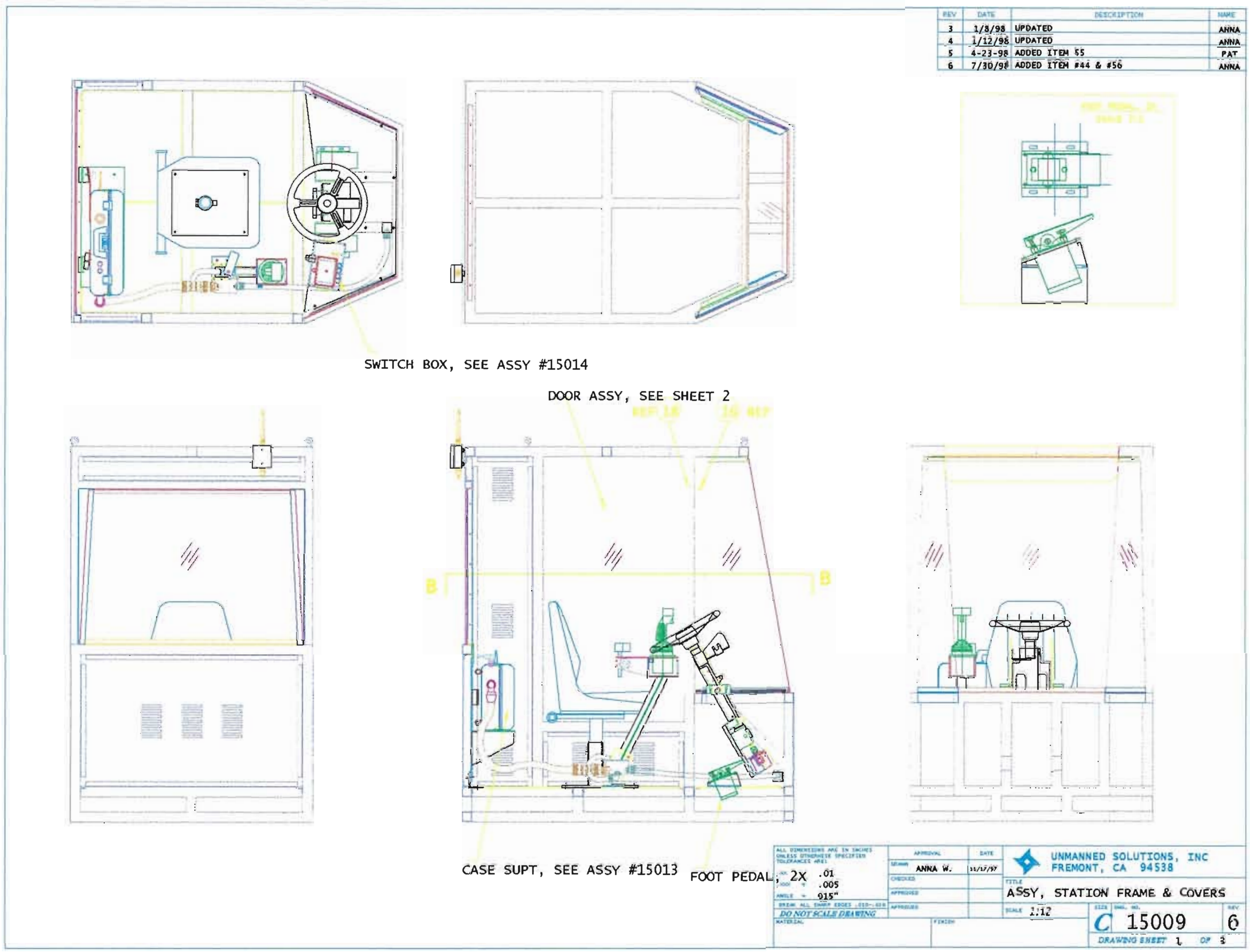


FIGURE A-8 SROU ASSEMBLY

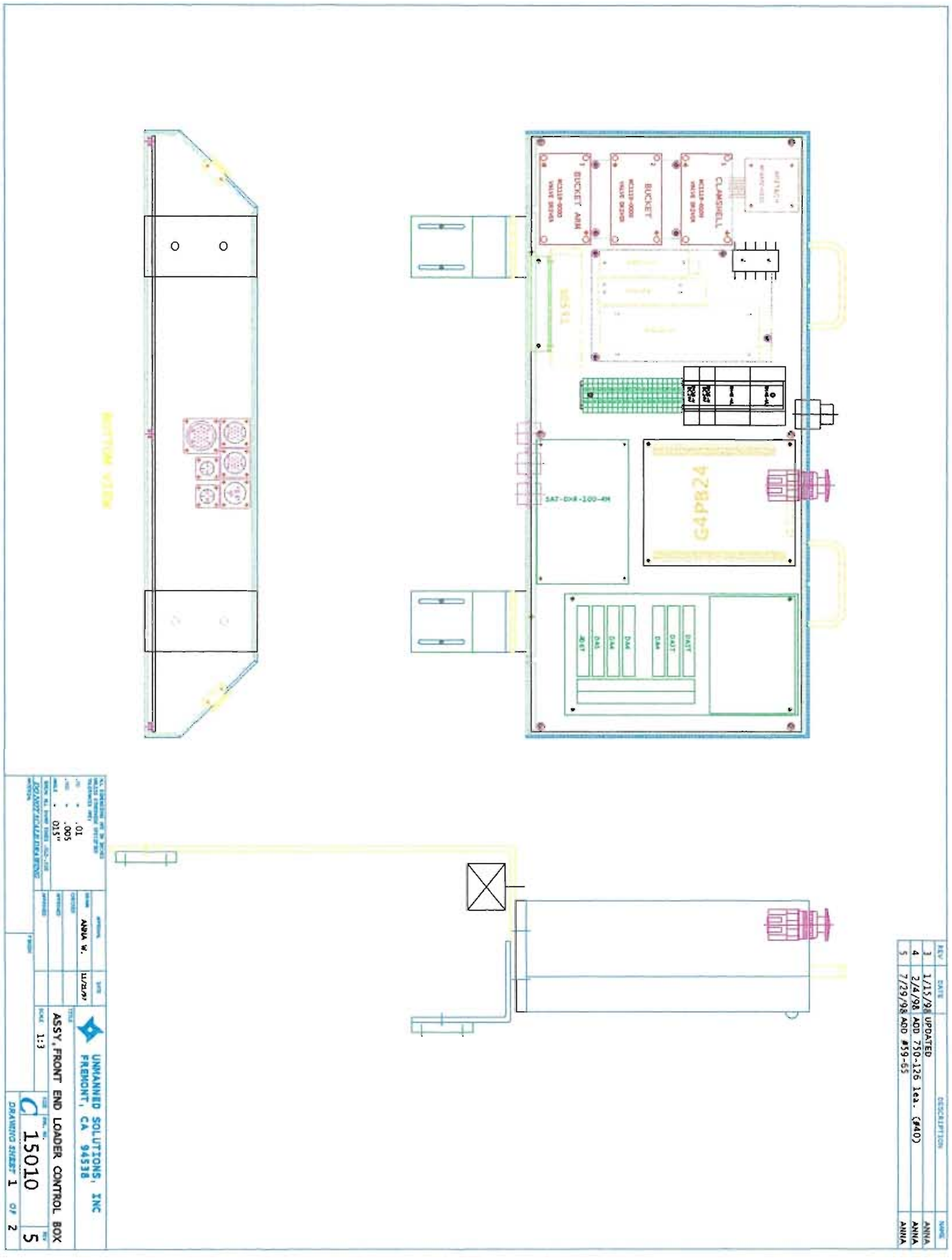
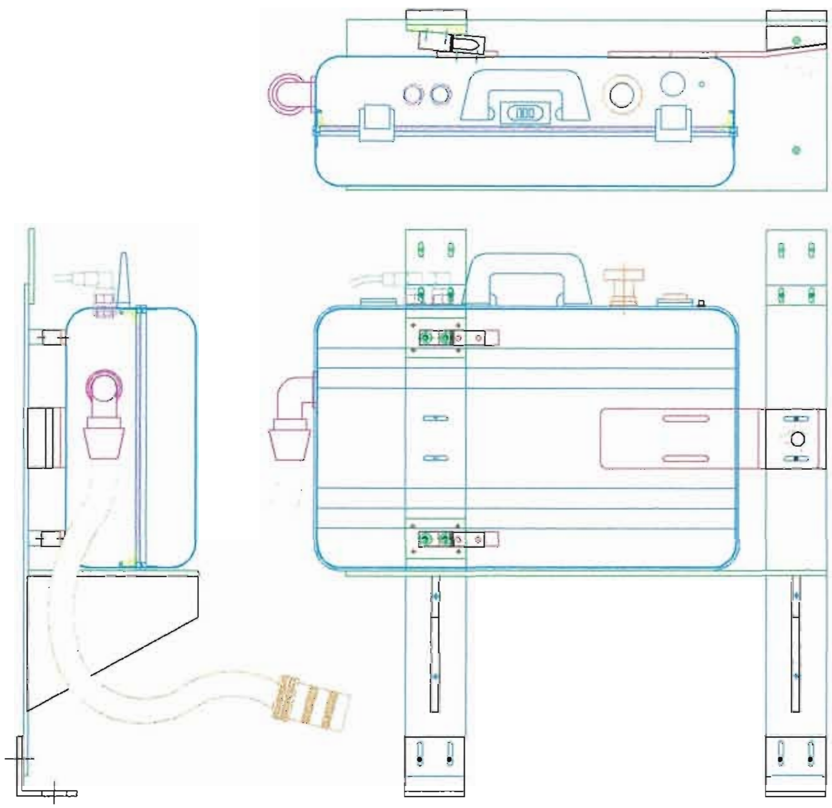


FIGURE A-9 FRONT END LOADER CONTROL BOX

REV	DATE	DESCRIPTION	NAME
2	1/29/98	ADDED PART 12	PFH



ITEM	PART NUMBER	DESCRIPTION	QTY
12	15063-002	PLATE 1	2
11	740-019	KNOB	1
10	355-022	HINGE	2
9	15130	SOC 2	1
8	15129	SOC 1	2
7	15128	TOP BRKT	2
6	15127	VERTICAL PL	2
5	15126	BOTTOM BRKT	2
4	15125	SHELF	1
3	15124	GUSSET	2
2	15063-001	PLATE 1	2
1	15062	STRAP 3	1

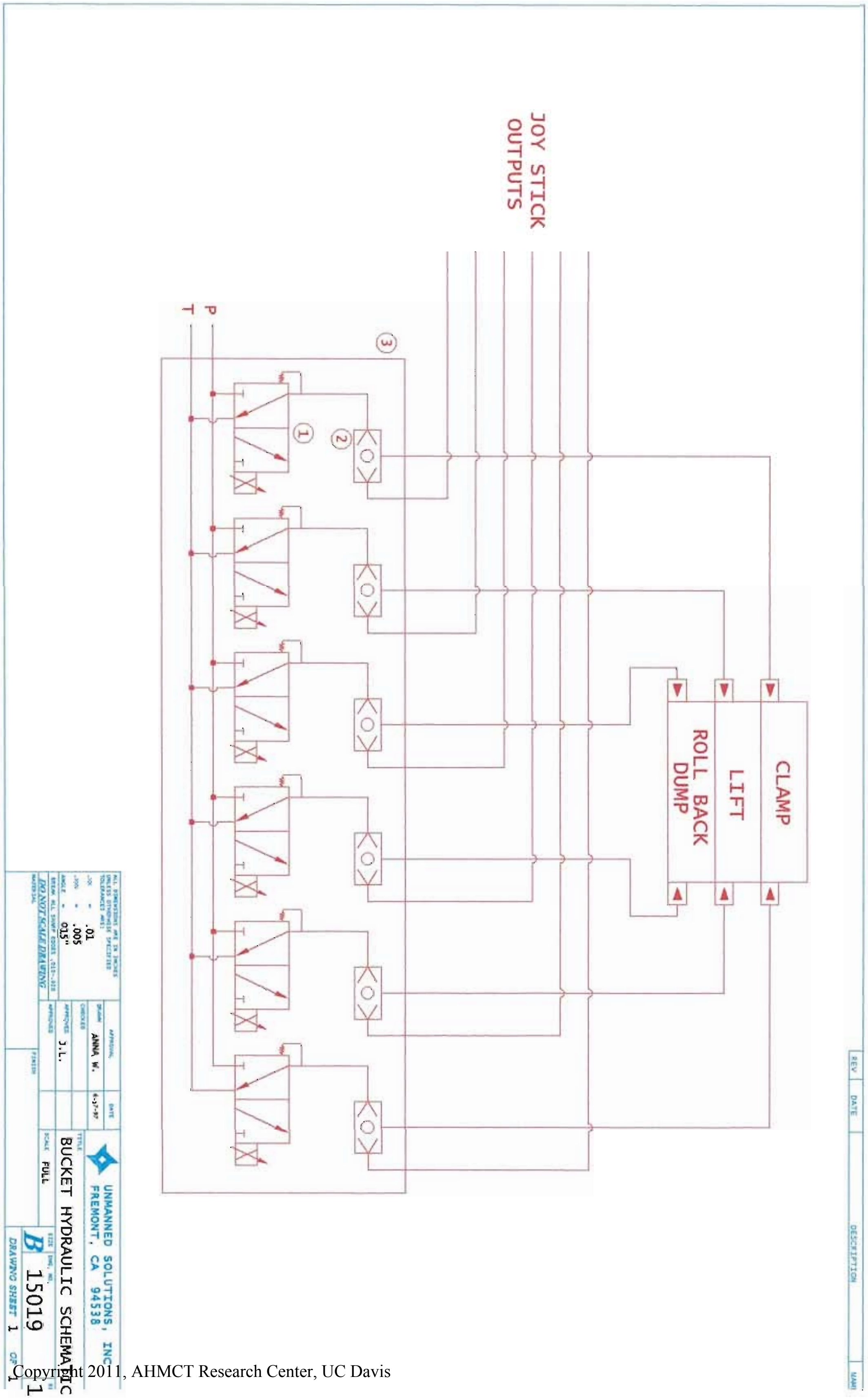
.XX = .020
.XXX = .005
ANGLE = 015"
DO NOT SCALE DRAWING
DRAWN ANNA W. 12/23/97
APPROVED DSH
UNMANNED SOLUTIONS, INC
FREMONT, CA 94538
TITLE ASSY, CASE SUPT, INSIDE STATION
SCALE 1 : 1.25
SIZE F DWG. NO. 15013 REV 2
DRAWING SHEET 1 OF 1

FIGURE A-10 SROU CONTROL BOX

APPENDIX B

HYDRAULIC SCHEMATICS

FIGURE B-1 BUCKET HYDRAULIC SCHEMATIC



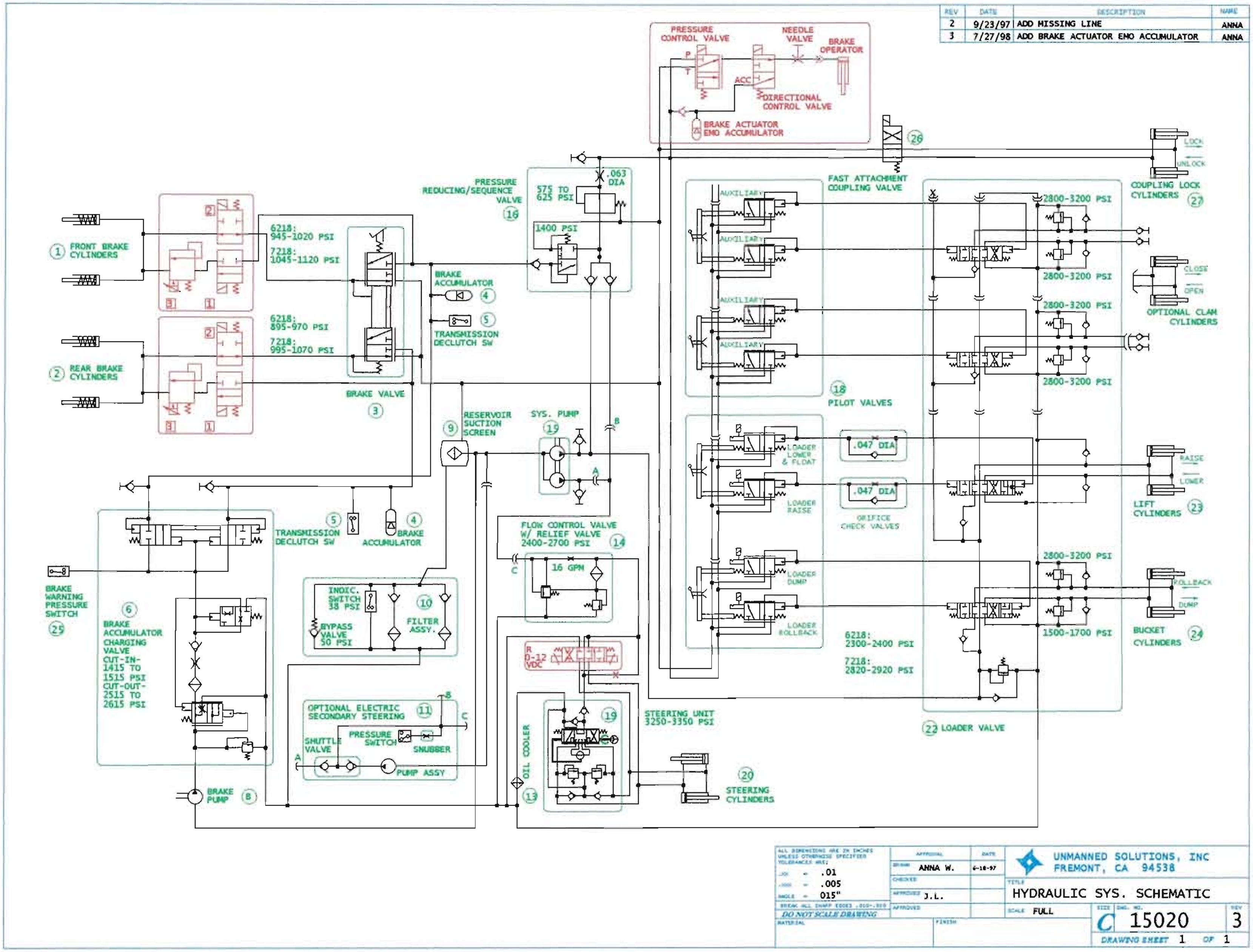
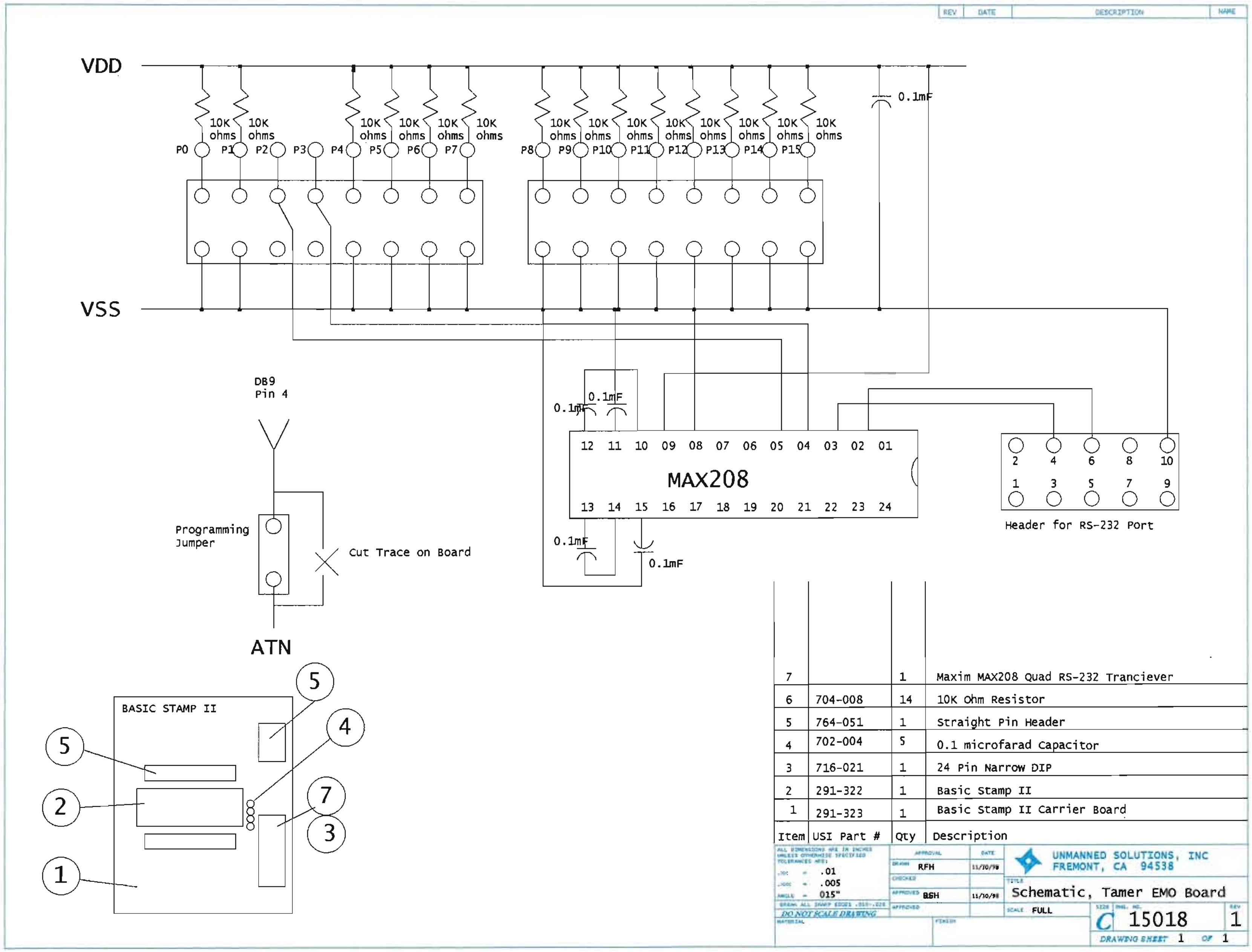


FIGURE B-2 SYSTEM HYDRAULIC SCHEMATIC

APPENDIX C

ELECTRICAL DRAWINGS

Unmanned solutions Inc.



Item	USI Part #	Qty	Description
7		1	Maxim MAX208 Quad RS-232 Tranciever
6	704-008	14	10K Ohm Resistor
5	764-051	1	Straight Pin Header
4	702-004	5	0.1 microfarad Capacitor
3	716-021	1	24 Pin Narrow DIP
2	291-322	1	Basic Stamp II
1	291-323	1	Basic Stamp II Carrier Board

FIGURE C-1 TAMER EMO BOARD