THE DUAL-ARM CAM-LOCK MANIPULATOR*

Ali Meghdari
Department of Mechanical & Aeronautical Engineering
University of California, Davis, CA. 95616

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ABSTRACT

This report presents the conceptual design and technical specifications of a novel robotics system termed as the Dual-Arm Cam-Lock Manipulator. It was designed on the basis of variable geometry, rigidity, and workspace. It has the ability to adjust its multi-arm structure in a compact configuration, making it suitable for applications requiring mobility. A telerobotics application of cam-lock manipulators has been proposed for bridge inspection and maintenance. Technical papers prepared on this subject has been accepted for presentation and publication at the 1994 ASCE SPACE conference on robotics for challenging environment, and the 1994 IEEE international conference on robotics and automation. In addition, an invention patent application has been filed with the office of technology transfer of the University of California.

CONCEPTUAL DESIGN AND CHARACTERISTICS OF A DUAL-ARM CAM-LOCK MANIPULATOR

Ali Meghdari †; Associate Professor, AHMCT Research Program
Department of Mechanical and Aeronautical Engineering
University of California-Davis, Davis, CA. 95616

ABSTRACT

Recent developments in the area of smart structures indicate that variable geometry/stiffness truss network is of fundamental importance in designing smart transformable structures and systems for space applications. This paper presents the conceptual and preliminary designs of a novel concept for a re-configurable dual-arm smart robotics structure named as the Dual-Arm Cam-Lock Manipulator *. It is designed to be capable of performing a wide variety of tasks by automatically re-configuring itself to form a variable geometry, stiffness, and workspace robotics structure. Hence, it may also be referred to as a Variable Geometry Robot Manipulator (VGRM).

I. INTRODUCTION

Performance requirements of advanced space structures and systems of the future have motivated a new approach in the design of robotics structures. This is mainly due to the fact that many orbital applications of robotics structures require adaptability to the changing conditions of operation (i.e. load, environment, etc.). These requirements can be formulated by automatic adaptability to changing conditions, such as changing and/or adjusting the geometry, workspace, stiffness, natural frequencies, etc. [1-2]. For this reason, a number of manipulator systems have been developed to overcome the limited performance of a manipulator with the aid of other manipulators or supporting structures [3-5].

In this paper, a new class of robots is introduced that employs fractal branching of its limbs in order to perform complex robotics tasks. The proposed dual-arm cam-lock manipulator shall be an actively controlled robotics structure containing sensors

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† **currently on sabbatical from the Sharif University of Technology, Tehran, Iran.**

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and actuators for structural and control functionality. It is defined as a class of highly redundant, multi-axis, multi-arm robot manipulator whose kinematics structure is somewhat fractal. Hence, fractal functions, such as the Weirstraus-Mandelbrot shall govern the structural branching of such an assembly and essentially define its kinematics structure [6]. The cam-lock robotics structure features a pair of multi-degree of freedom planar arms jointed together at a sharing base. It is capable of forming a stronger arm with variable rigidity/geometry by the virtue of a passive cam-lock mechanism incorporated at each joint . For example, two five degree-of-freedom planar arms may be braced together by the first three links from the base to form a more rigid robotics structure with two arms at the distal end of the third zipped links, each maintaining two independent degrees of freedom. The trick lies within the geometrical design of the manipulator links, joints, and the cam-lock mechanism that are briefly discussed in this article. Due to the existing similarities in geometry of the designed linkages with those of the cam mechanisms, the term *Cam-Lock* was chosen to describe it. This type of manipulator may be a fine example for deployable space structures. It has the ability to adjust its structure in a controlled fashion in order to develop compatible configurations during the deployment. It could further find application as an space crane for the assembly of large systems in space. In addition, a Telerobotics application of cam-lock manipulators for highway bridge inspection and maintenance is also proposed.

II. DUAL ARM MANIPULATORS

Without much exaggeration, one may claim that most of the suitable tasks in nature generally take place by the virtue of one or more dual or paired mechanisms. Natural motions of the human limbs and organs (hands, fingers, legs, eyes, ears, etc.) as well as the wings of birds, and the fins of fish clearly indicate the importance of paired or dual mechanisms for an optimal performance. In situations where part of a pair is lost or no longer functional, its importance becomes more and more evident.

It is therefore recognized by robotics engineers and scientists that multiple cooperative manipulators shall be capable of performing tasks that are either difficult or impossible to perform by a single manipulator. These tasks include manipulation and transportation of heavy, long, large, or flexible objects. In contrast, executing a task with two or more collaborating arms is much more difficult, due to the mutual effects associated with their dynamics, kinematics, interface and collision possibility.

In general terms, a dual arm manipulator is defined as a mechanism in which its elements are basically a mirror image of each other with respect to a pre-defined axis/plane of symmetry. A dual-arm manipulator is composed of two multi-link open-loop kinematics chains as shown schematically in Figure 1, where (θ_{Ri}, L_{Ri} ; i=1,2,...,n), and (θ_{Lj}, L_{Lj}; j=1,2,...,m) are the joint angles and the link lengths of the Right and the Left manipulators, respectively. Human limbs configurations may serve as fine examples for the way these elements are positioned relative to each other.

As shown in the Figure 2, although a dual arm manipulator typically forms a closed kinematical chain, it may have a more general form of topologies as either an open-chain, a closed-chain, or a hybrid-chain. Furthermore, it can generally posses a motion configuration in a symmetric, and non-symmetric fashion with respect to a pre-defined axis of symmetry.

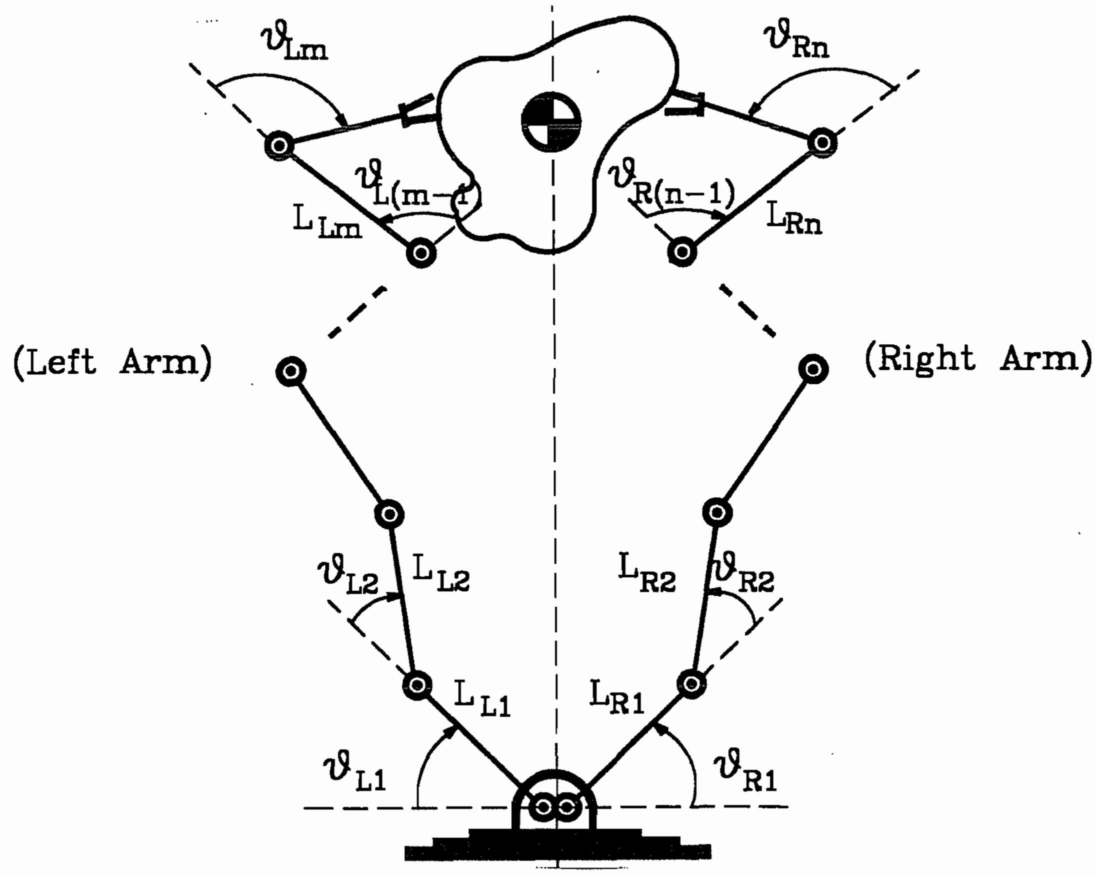
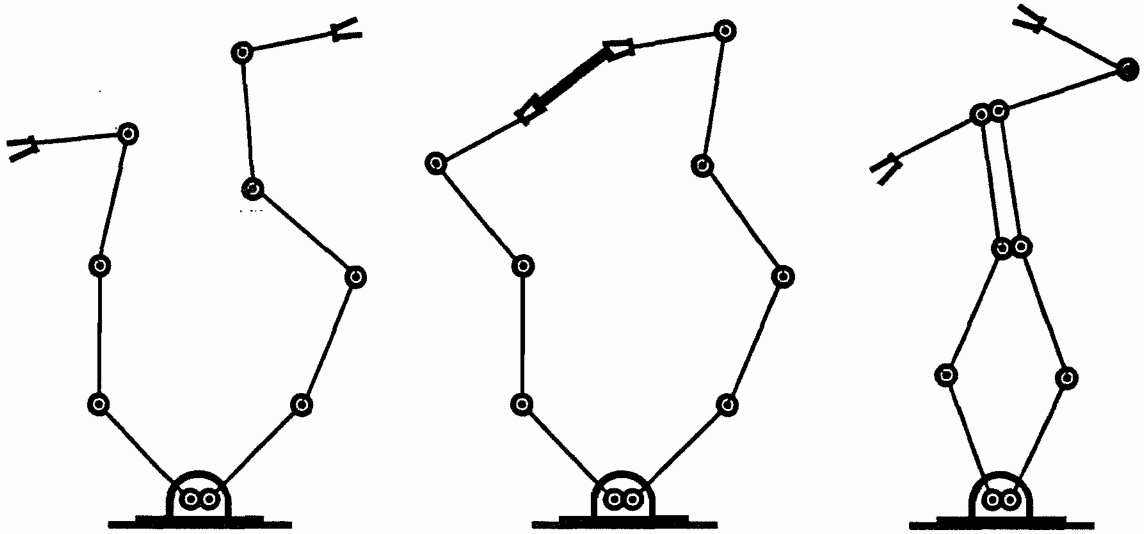


Figure 1. Schematics of a dual-arm manipulator.



(a) open-chain (b) closed-chain (c) hybrid-chain

Figure 2. Motion configurations of a dual arm manipulator.

III. THE CAM-LOCK MECHANISM.

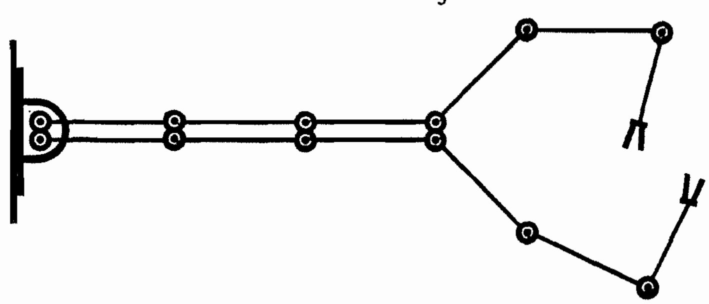
As mentioned previously, geometrical configuration, mobility, degree of rigidity, and the workspace of a dual-arm manipulator is changed when some of the joints and links in both arms are braced together in an appropriate fashion.

Consider a multi-degree of freedom dual-arm manipulator with uniform links and joints as shown in Figure 3. For simplicity consider both arms having an equal number of joints and links with uniform properties. Furthermore, let the joints and links bracing's be performed in a symmetric fashion. In situations where at least a single joint and link of either arm is braced with a single joint and link of the other arm such that no relative motion among the zipped links is possible, the *Cam-Lock Mechanism* is observed (mechanical, or electromagnetic means may be used for this purpose). Hence, when the i-th joint and link of the right arm is cam-locked with the j-th joint and link of the left arm, a new dual-arm manipulator is formed. Clearly, the overall mobility of the dual-arm manipulator is solely affected by the locking mechanism and the new arm shall maintain different characteristics. Figure 3 displays a dual-arm planar manipulator with each arm having six independent degrees of freedom in the originally unlocked (free) configuration. They are cam-locked at different locations throughout the arm, reducing the overall mobility, and hence, increasing the overall rigidity of the robotics structure. The following relation presents an elementary analogy for the mobility of each arm in the presence of cam-locking:

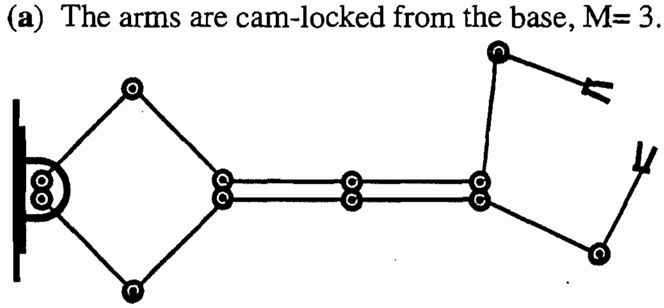
$$M = 3(n - 1 - c) - 2(j - c) \quad (1)$$

where;

M: is the overall mobility for each arm,
n: is the number of links including the ground for each arm,
j: is the number of one-degree-of-freedom joints,
c: is the number of cam-locked links and joints.

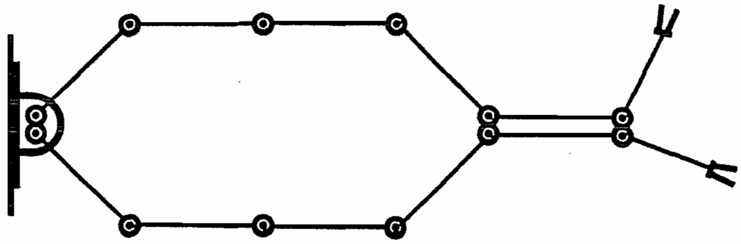


(a) The arms are cam-locked from the base, M= 3.

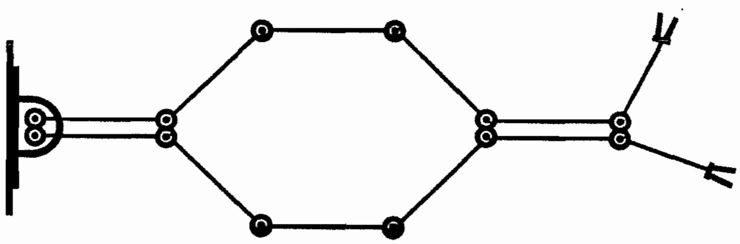


(b) The arms are cam-locked in the middle, M= 4.

Figure 3. The cam-locked configurations of a dual-arm manipulator (cont. →).



(c) The arms are cam-locked at the wrist, M= 5.



(d) The arms are cam-locked at the base and the wrist, M= 4.

Figure 3. The cam-locked configurations of a dual-arm manipulator.

IV. THE DUAL-ARM CAM-LOCK MANIPULATOR

Of particular interest in the present paper is to establish the conceptual design features of the cam-lock manipulator. For the sake of analysis, two of the most recent designs have been studied and prototypes are fabricated. Figure 4 presents computerized solid models of a dual-arm cam-lock manipulator that may undergo large controlled changes from a compact to an unfolding geometrical configuration. This could be a fine example for deployable space structures. It has the ability to adjust its structure in a controlled fashion in order to develop compatible configurations during the deployment. It could further find application as an space crane for the assembly of large systems in space. These two models differ in the sense that in the one shown in Figure 4(a), cam-locking occurs in the middle of each link, requiring the presence of an offset between the respective joints and links of both arms. This offset has been eliminated in the second design shown in Figure 4(b), thereby creating compatible features among the respective joints and links in both arms. Figure 5 presents the cam-shaped drawings of the links in both manipulator assemblies. One should note that the locking location may be moved along the link in order to achieve various strength and stability so long as the condition $r_1 + r_2 < L$ is met. Link parameters r_1, r_2 are shown in Figure 5, with L being the link's length. Satisfying this condition would greatly increase the range of motion of each link in the assembly. Figure 6 displays the general sub-assembly drawing of a dual arm (each having three joints) cam-lock manipulator.

In addition to space applications, cam-lock manipulators may also find applications in autonomous road construction and maintenance technology. In particular; one may consider them for inspection of bridge decks, handling of large and heavy loads and structures, etc. Figure 7 shows a possible telerobotics application of such manipulators in bridge inspection and maintenance. Finally, Figure 8 displays several prototypes of dual-arm cam-lock manipulators fabricated for further analysis.

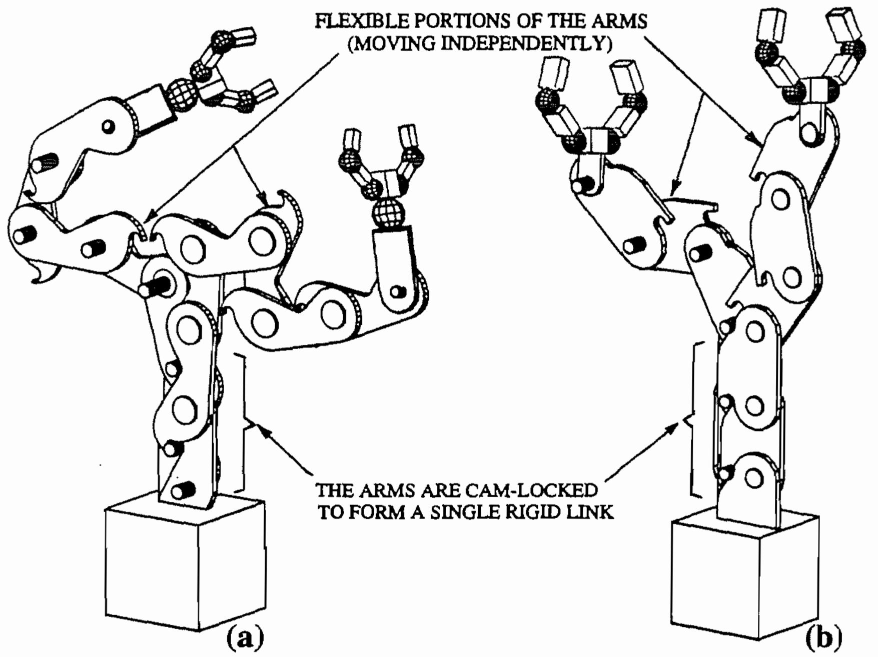
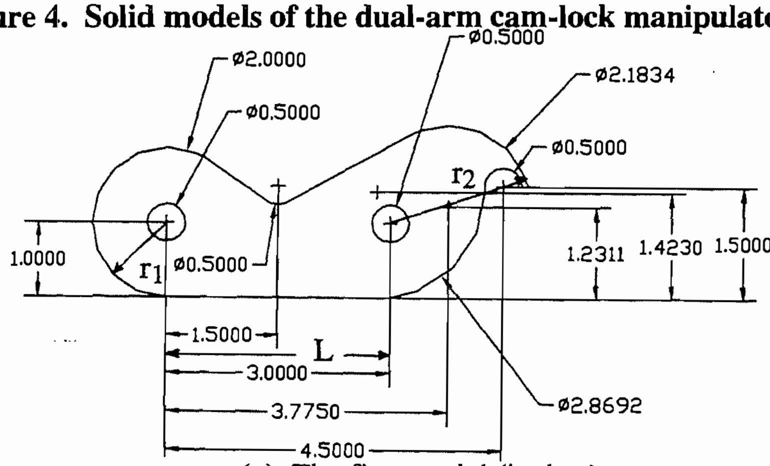
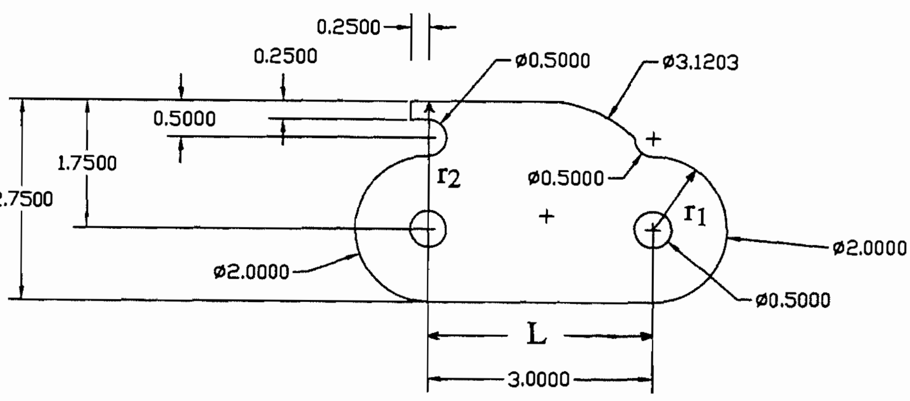


Figure 4. Solid models of the dual-arm cam-lock manipulators.

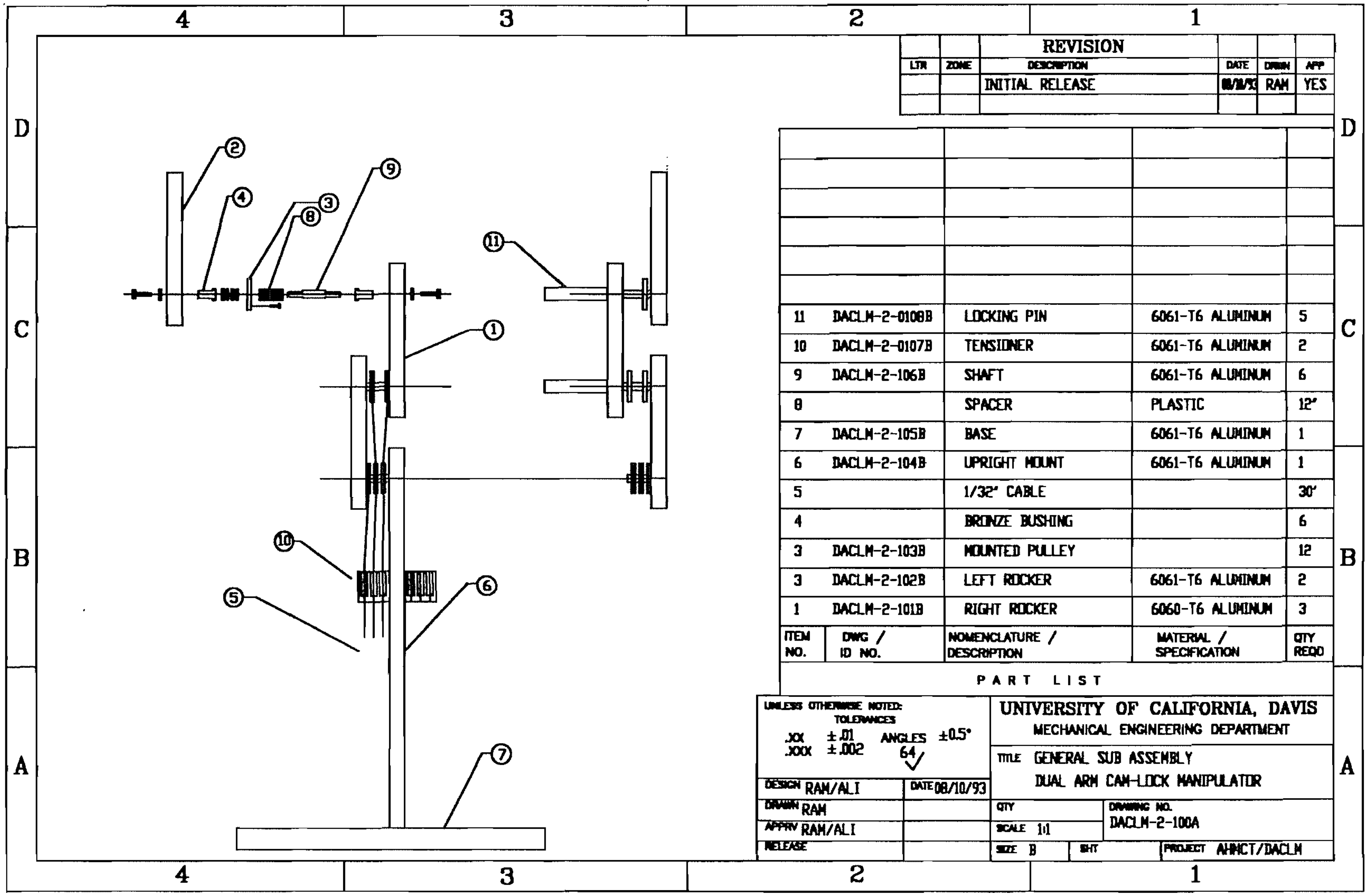


(a) The first model (inches).



(b) The second model (inches).

Figure 5. The cam-lock manipulator link designs.



ITEM NO.	DWG / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD
11	DACLM-2-0108B	LOCKING PIN	6061-T6 ALUMINUM	5
10	DACLM-2-0107B	TENSIONER	6061-T6 ALUMINUM	2
9	DACLM-2-106B	SHAFT	6061-T6 ALUMINUM	6
8		SPACER	PLASTIC	12"
7	DACLM-2-105B	BASE	6061-T6 ALUMINUM	1
6	DACLM-2-104B	UPRIGHT MOUNT	6061-T6 ALUMINUM	1
5		1/32" CABLE		30'
4		BRONZE BUSHING		6
3	DACLM-2-103B	MOUNTED PULLEY		12
3	DACLM-2-102B	LEFT ROCKER	6061-T6 ALUMINUM	2
1	DACLM-2-101B	RIGHT ROCKER	6060-T6 ALUMINUM	3

Figure 6. General sub-assembly drawing of a dual-arm cam-lock manipulator.

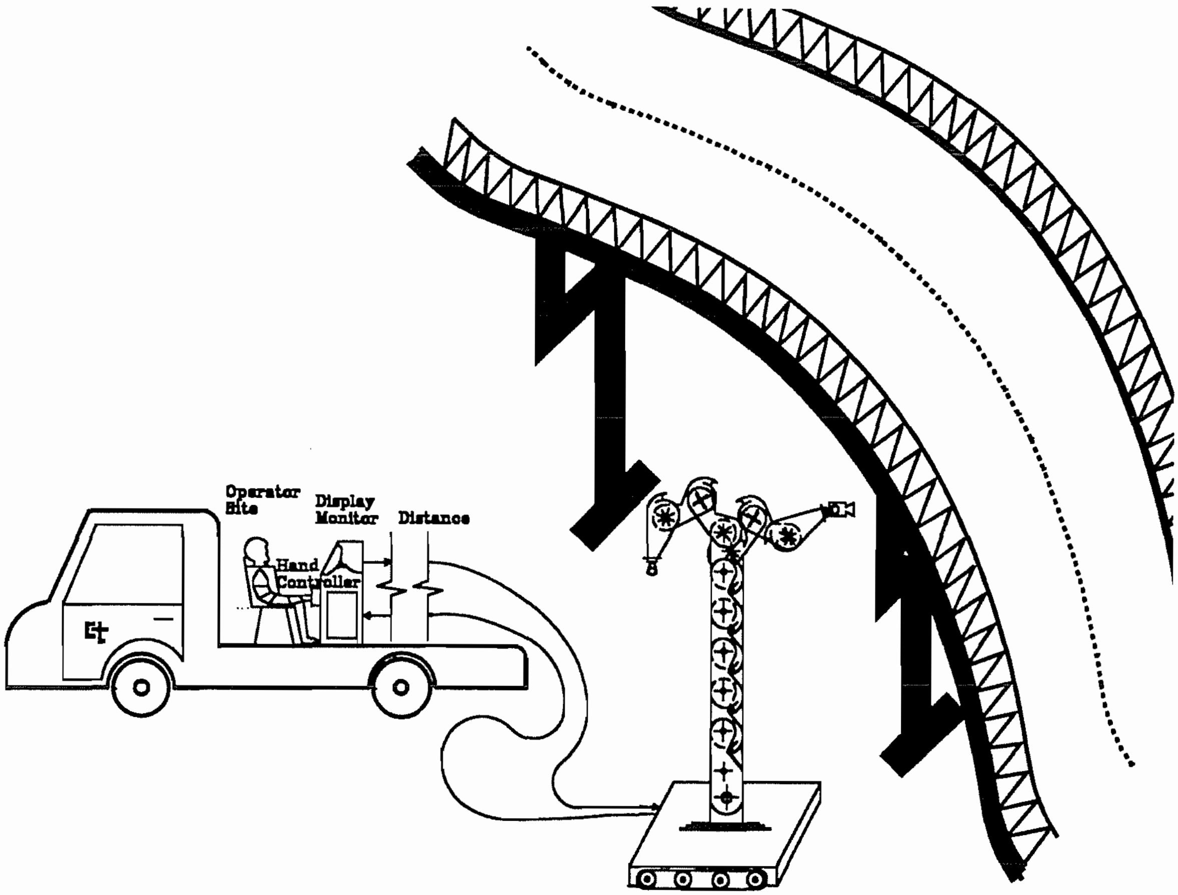
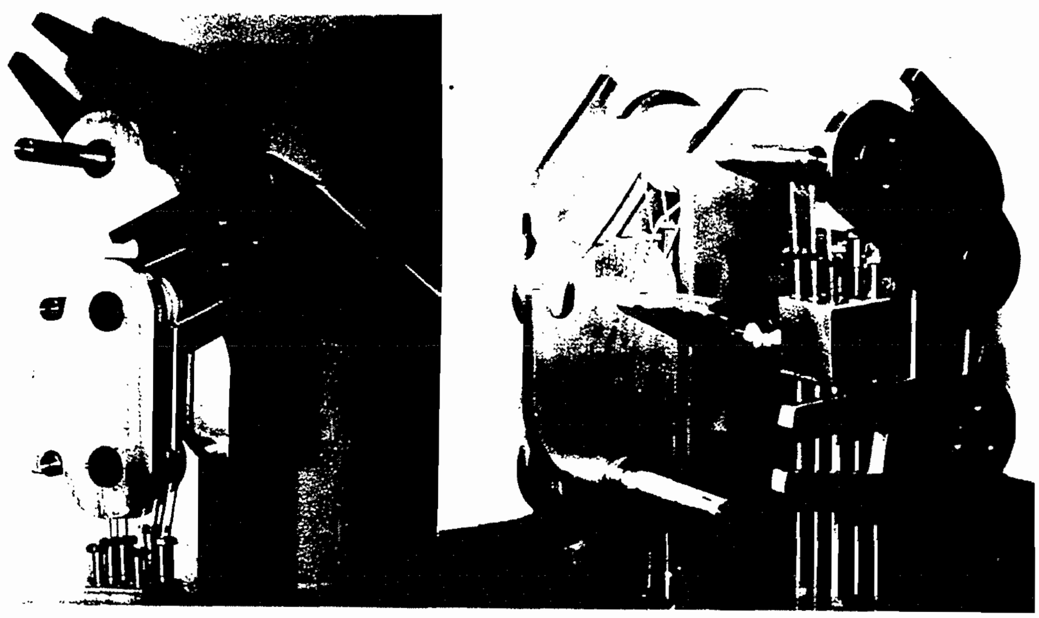
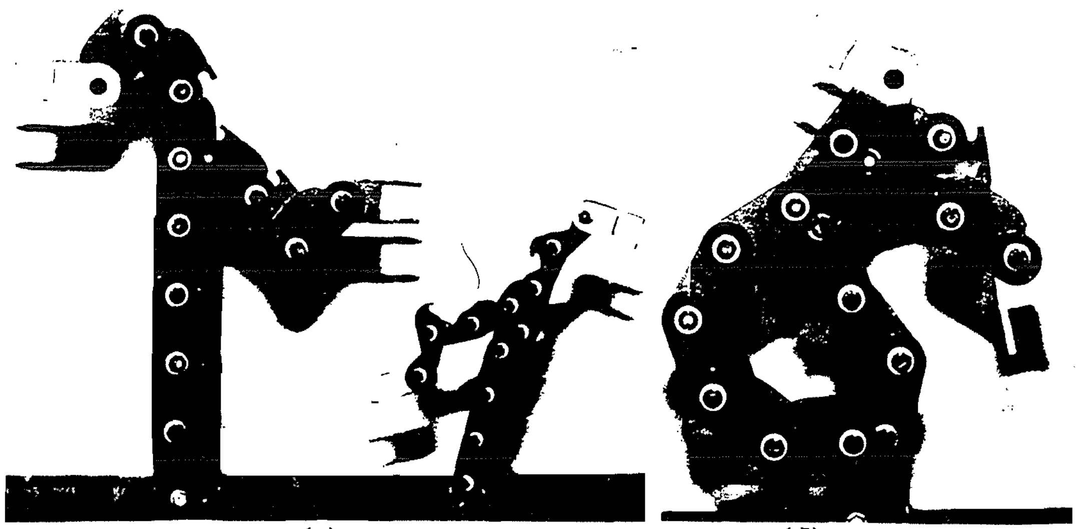


Figure 7. Telerobotics application of cam-lock manipulators in bridge inspection.



(a) (b)

Figure 8. Prototypes of both models in various configurations(cont. →) .



(c) (d)

Figure 8. Prototypes of both models in various configurations.

V. CONCLUSIONS

Preliminary design features and characteristics of a new class of robotics structure named as the Dual-Arm Cam-Lock Manipulator has been presented. The cam-lock mechanism was considered at two different locations along the links. The cam-lock location could be optimized for various designs and performance. A mobility analysis of such a manipulator for various geometrical configurations was performed and the result is promising. Further research on the kinematics and dynamics issues of this manipulator is presently underway and will be reported in a following paper.

ACKNOWLEDGMENTS:

This work was supported in part by the office of research and industrial relations of the Sharif university of technology, and the California Department of Transportation (CalTrans) through the Advanced Highway Maintenance and Construction Technology (AHMCT) program at the University of California-Davis. My thanks to Mr. Richard A. McGrew for helping with the fabrication process.

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SPACE 94

The 4th International Conference and Exposition on Engineering, Construction, and Operations in Space and The Conference and Exposition/Demonstration on Robotics for Challenging Environments

Albuquerque, New Mexico February 26 - March 3, 1994

June 9, 1993

Ali Meghdari
Department of Mechanical, Aeronautical, and Materials Engineering
University of California, Davis
Davis, CA 95616

Dear author:

The technical review committee is pleased to inform your abstract entitled "Conceptual Design and Characteristics of a Dual-Arm Cam-Lock Robotics System" has been accepted for the ASCE Specialty Conference on Robotics for Challenging Environments. Full papers are due August 1. Please note that this is a firm deadline!

Information on preparation of full papers will be sent to you directly from ASCE. In addition, within the next few weeks you will receive a list of technical sessions and the papers assigned to them. If you have any questions on paper presentation or on the conference in general, please contact one of us.

Thank you for helping to make the Conference on Robotics for Challenging Environments a success. We look forward to seeing you in Albuquerque next spring.

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Berkeley, CA 94720
FAX: (510) 643-8928
Phone: (510) 642-1927
demsetz@ce.berkeley.edu

Paul Klarer
Department 9616
Sandia National Laboratories
PO 5800
Albuquerque, NM 87185
FAX: (505) 844-5946
Phone: (505) 844-2900
prklarer@isrc.sandia.gov

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CONCEPTUAL DESIGN AND DYNAMICS MODELING OF A COOPERATIVE DUAL-ARM CAM-LOCK MANIPULATOR

Ali Meghdari †; Associate Professor, AHMCT Research Program
University of California-Davis
Department of Mechanical and Aeronautical Engineering
Davis, California 95616

ABSTRACT:

Recent developments in the area of smart structures indicate that variable geometry/stiffness truss network is of fundamental importance in designing smart transformable structures and systems for space applications. This paper presents the conceptual designs and dynamics modeling of a cooperative re-configurable dual-arm smart robotics structure named as the Dual-Arm Cam-Lock Manipulator *. The manipulator is designed to be capable of performing a wide variety of tasks by automatically re-configuring itself to form a variable geometry, stiffness, and workspace robotics structure. Hence, it may also be referred to as a Variable Geometry Robot Manipulator (VGRM).

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Performance requirements of advanced space structures and systems of the future have motivated a new approach in the design of robotics structures. This is mainly due to the fact that many orbital applications of robotics structures require adaptability to the changing conditions of operation (i.e., load, environment, etc.). These requirements can be formulated by automatic adaptability to changing conditions, such as changing and/or adjusting the geometry, workspace, stiffness, natural frequencies, etc. [1-3]. For this reason, a number of manipulator systems have been developed to overcome the limited performance of a manipulator with the aid of other manipulators or supporting structures [4-6].

In this paper, a new class of robots is introduced that employs fractal branching of its limbs in order to perform complex robotics tasks. The proposed dual-arm cam-lock manipulator shall be an actively controlled robotics structure containing sensors and actuators for structural and control functionality. It is defined as a class of highly redundant, multi-axis, multi-arm robot manipulator whose kinematics structure is somewhat fractal. Hence, fractal functions, such as the Weirstraus-Mandelbrot shall govern the structural branching of such an assembly and essentially define its kinematics structure [7]. The cam-lock robotics structure features a pair of multi-degree of freedom planar arms jointed together at a sharing base. It is capable of forming a stronger arm with variable rigidity/geometry by the virtue of a passive cam-lock mechanism incorporated at each joint . The trick lies within the geometrical design of the manipulator links, joints, and the cam-lock mechanism that are briefly discussed in this article[1]. The term cam-lock is adapted due to the existing similarities in geometry of the designed linkages with those of the cam mechanisms. This type of manipulator may be a fine example for deployable space structures. It has the ability to adjust its structure in a controlled fashion in order to develop compatible configurations during the deployment. It could further find application as a space crane for the assembly of large systems in space. In addition, a Telerobotic application of cam-lock manipulators for highway bridge inspection and maintenance is also proposed.

II. DUAL ARM MANIPULATORS

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As displayed in Figure 2, although a dual arm manipulator typically forms a closed kinematical chain, it may have a more general form of topologies as either an open-chain, a closed-chain, or a hybrid-chain. Furthermore, it can also posses a motion configuration in a symmetric, and non-symmetric fashion with respect to a pre-defined axis of symmetry.

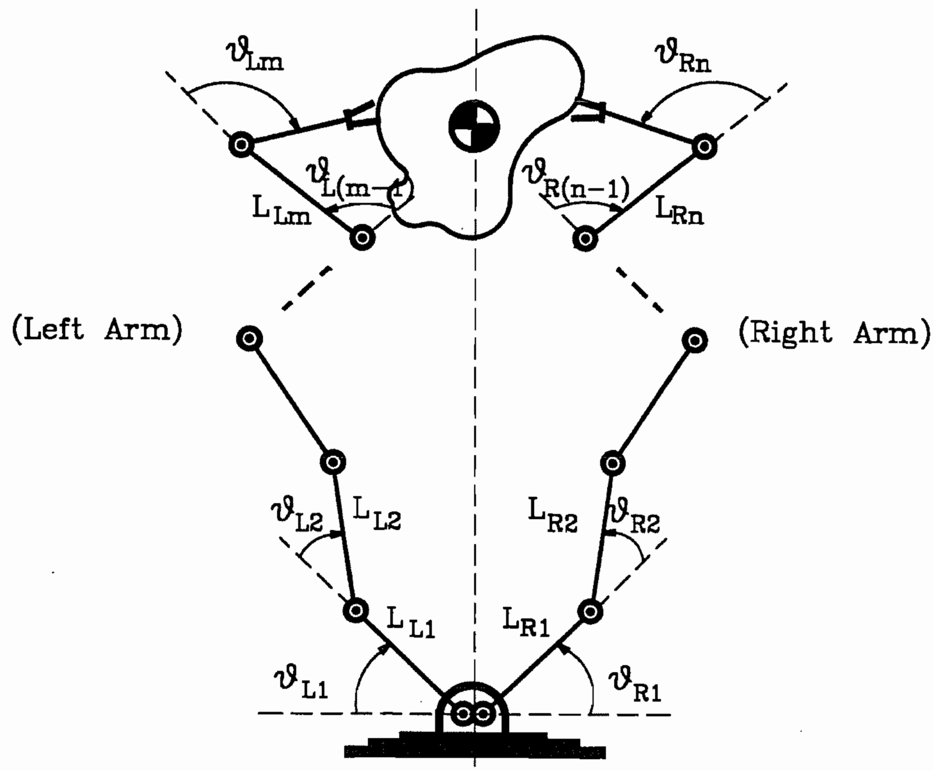
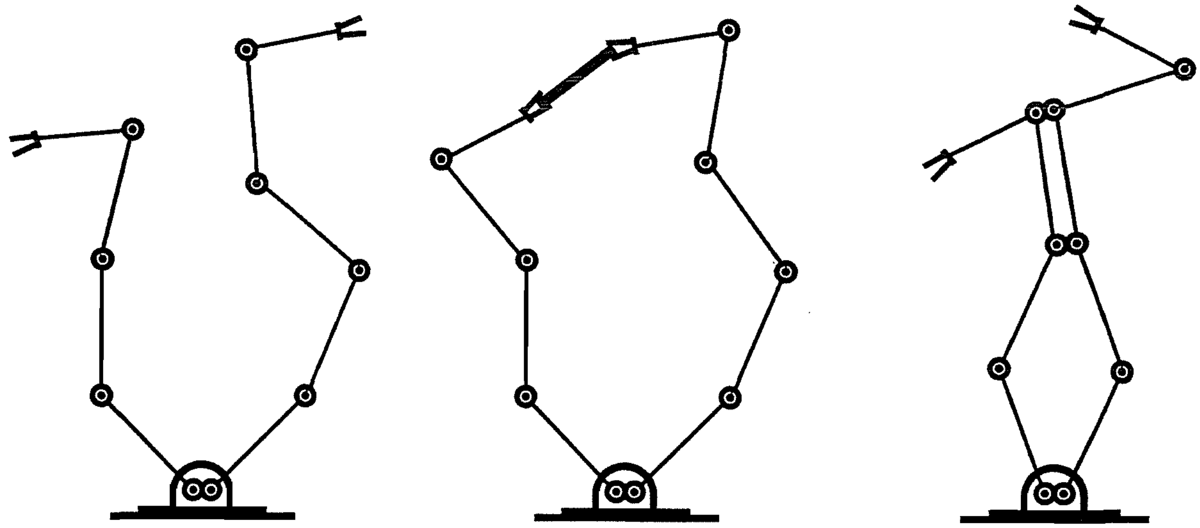


Figure 1. Schematics of a dual-arm manipulator.



(**a**) open-chain (**b**) closed-chain (**c**) hybrid-chain

Figure 2. Motion configurations of a dual-arm manipulator.

III. THE DUAL-ARM CAM-LOCK MANIPULATOR

As mentioned previously, geometrical configuration, mobility, degree of rigidity, and the workspace of a dual-arm manipulator is changed when some of the joints and links of the arms are braced together in an appropriate fashion.

Consider a multi-degree of freedom dual-arm manipulator with uniform links and joints as shown in figure 3. For simplicity consider both arms having an equal number of joints and links with similar properties. Furthermore, let the joints and links bracing's be performed in a symmetric fashion. In situations where at least a single joint and link of either arm is braced with a single joint and link of the other arm such that no relative motion among the zipped links is possible, the *Cam-Lock Mechanism* is observed. Hence, when the i-th joint and link of the right arm is cam-locked with the j-th joint and link of the left arm, a new dual-arm manipulator is formed. Clearly, the overall mobility of the dual-arm manipulator is solely affected by the locking mechanism and the new arm shall maintain different characteristics. Figure 3 displays a dual-arm planar manipulator with each arm having six independent degrees of freedom in the originally unlocked (free) configuration. They are cam-locked from the base of the manipulator, reducing its mobility, and hence, increasing the overall rigidity of the robotics structure. The following relation governs the mobility of each arm in the presence of the cam-locking mechanism:

$$M = 3(n - 1 - c) - 2(j - c) \qquad (1)$$

where;

M: is the overall mobility for each arm,

n: is the number of links including the ground for each arm,

j: is the number of one-degree-of-freedom joints,

c: is the number of cam-locked links and joints.

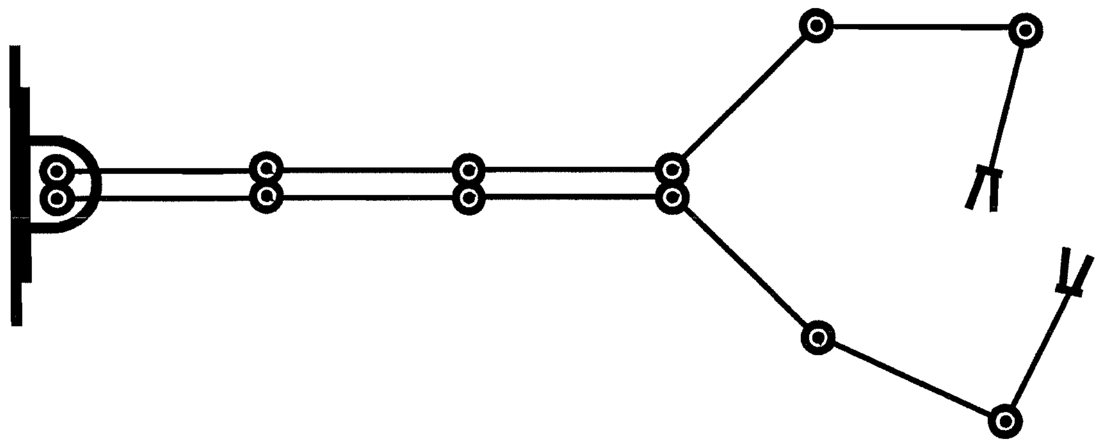


Figure 3. The cam-lock configuration of a dual-arm manipulator, M = 3.

By now you may have wondered that why the term cam-lock has been chosen to describe this manipulator. This terminology was solely adapted due to the existing similarities in geometry of the designed linkages with those of the cam mechanisms (see Figures 4-7).

Of particular interest in the present paper is to establish the conceptual design features of the cam-lock manipulator. For the sake of analysis, two of the most recent designs have been studied and prototypes are fabricated[1]. Figure 4 presents computerized solid models of a dual-arm cam-lock manipulator that undergo large controlled changes from a compact to an unfolding geometrical configuration. This may be a fine example for deployable space structures. It has the ability to adjust its structure in a controlled fashion in order to develop compatible configurations during the deployment. These two models differ in the sense that in the one shown in Figure 4(a), cam-locking occurs in the middle of each link, requiring the presence of an offset between the respective joints and links of both arms. However, in the second design shown in Figure 4(b), this offset has been eliminated, thereby creating compatible features among the respective joints and links in both arms. Figure 5 presents the cam-shaped drawings of the links in both manipulators. It should be noted that the locking location may be moved along the link to achieve various strength and stability so long as the condition $\mathbf{r}_1 + \mathbf{r}_2 < L$ is met. Link parameters $\mathbf{r}_1$ and $\mathbf{r}_2$ are shown in Figure 5, with L being the link's length. Satisfying this condition would greatly increase the range of motion of each link in the assembly.

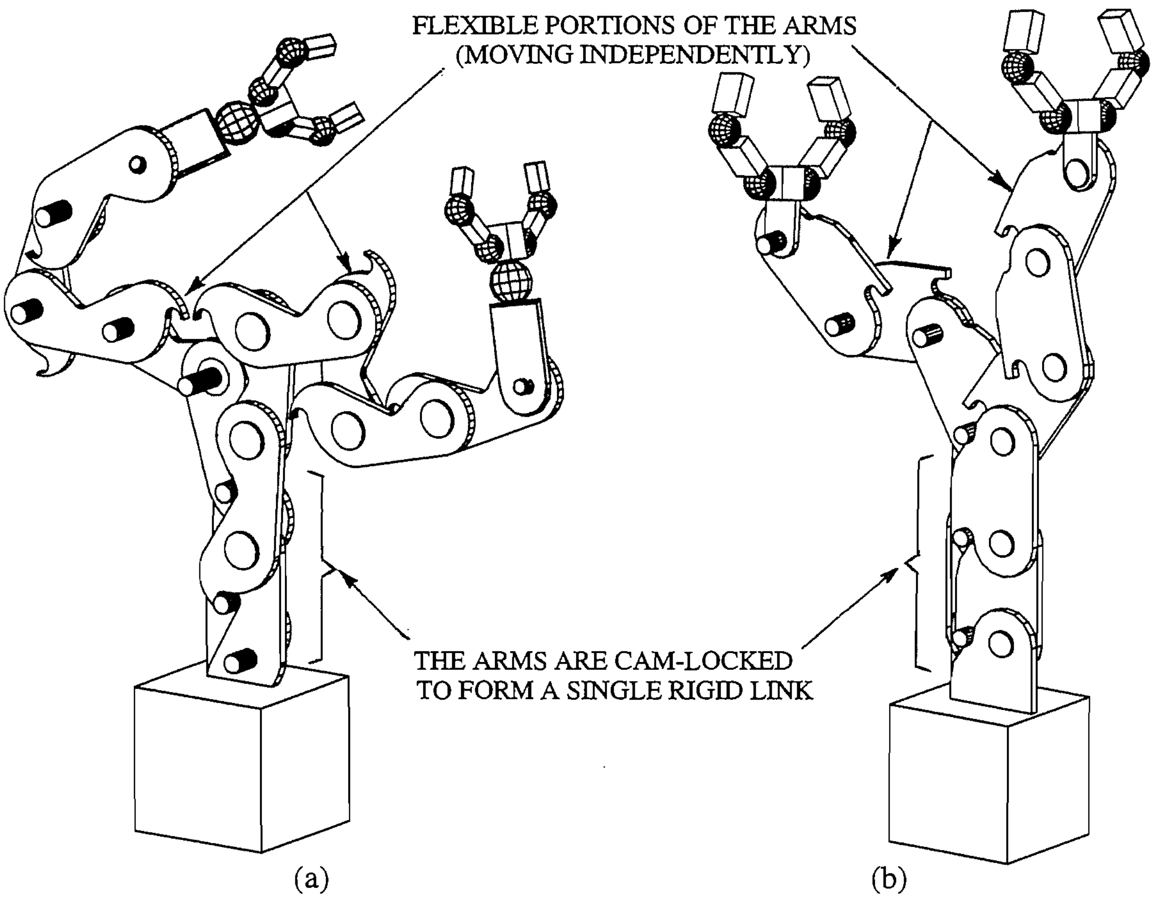
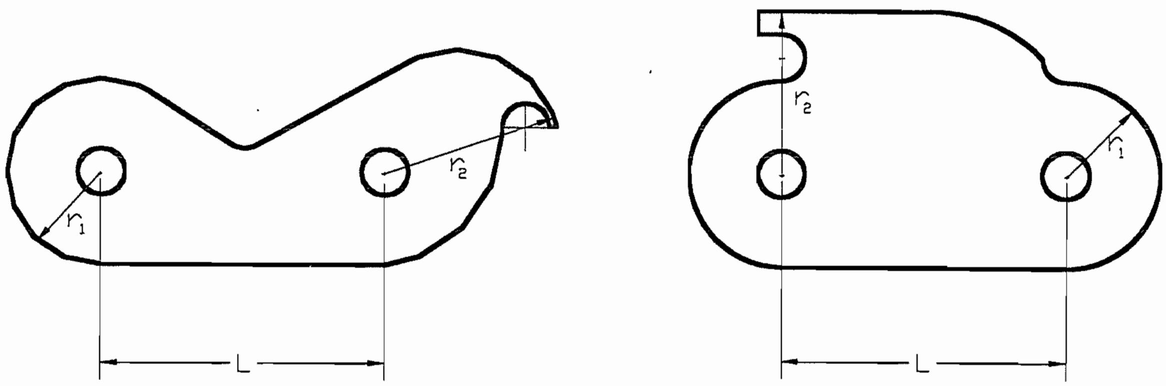


Figure 4. Solid models of the dual-arm cam-lock manipulators.

In addition to space applications, cam-lock manipulators may also find applications in autonomous road construction and maintenance technology. In particular; one may consider them for inspection of bridge decks, handling of large and heavy loads and structures, etc. Figure 6 displays a possible telerobotics application of such a manipulator for bridge inspection and maintenance. Figure 7 presents prototypes of dual-arm cam-lock mechanisms fabricated for further analysis.



(a) The first model. (b) The second model.

Figure 5. The cam-lock manipulator links designs.

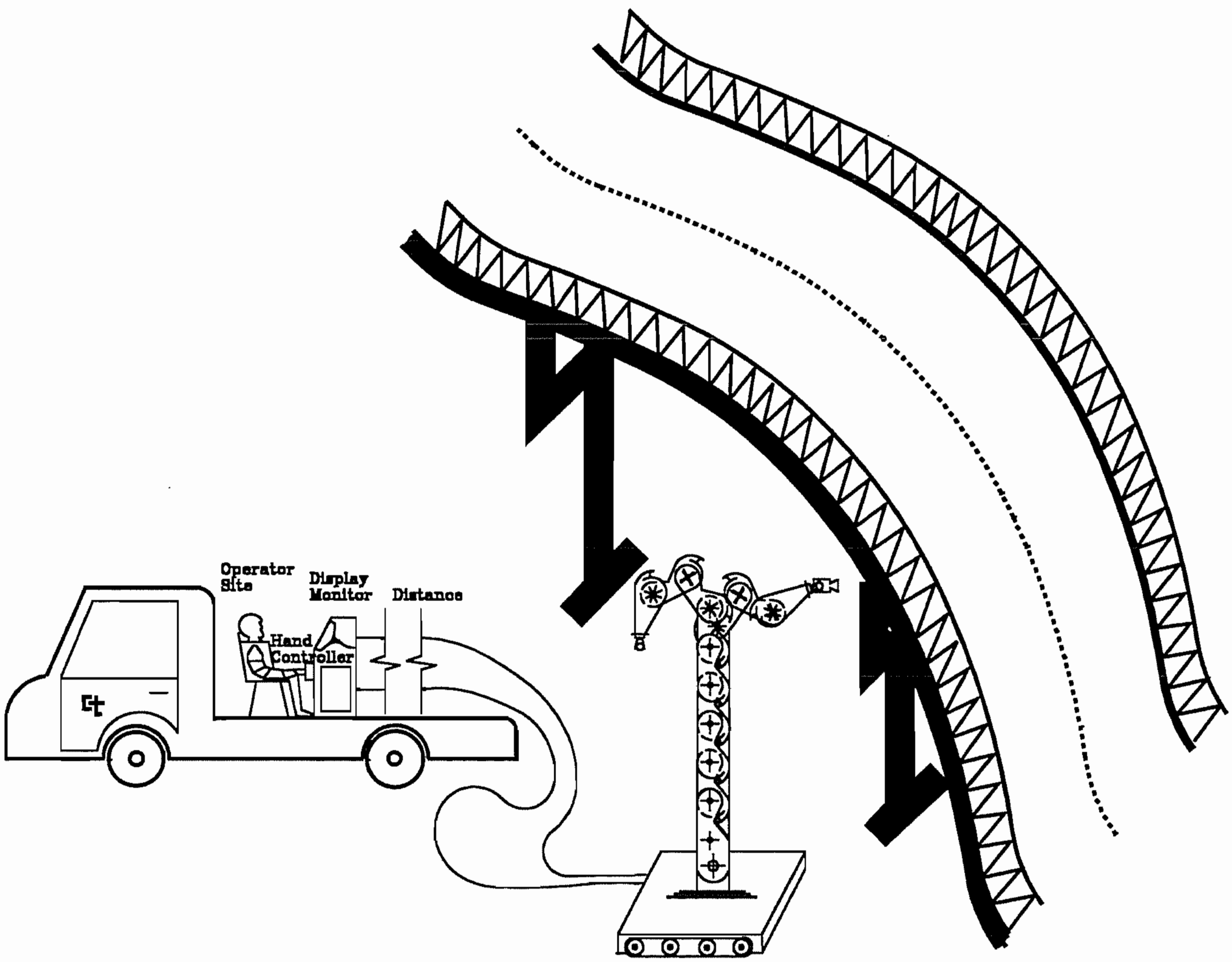


Figure 6. Telerobotics application of cam-lock manipulators in bridge inspection.

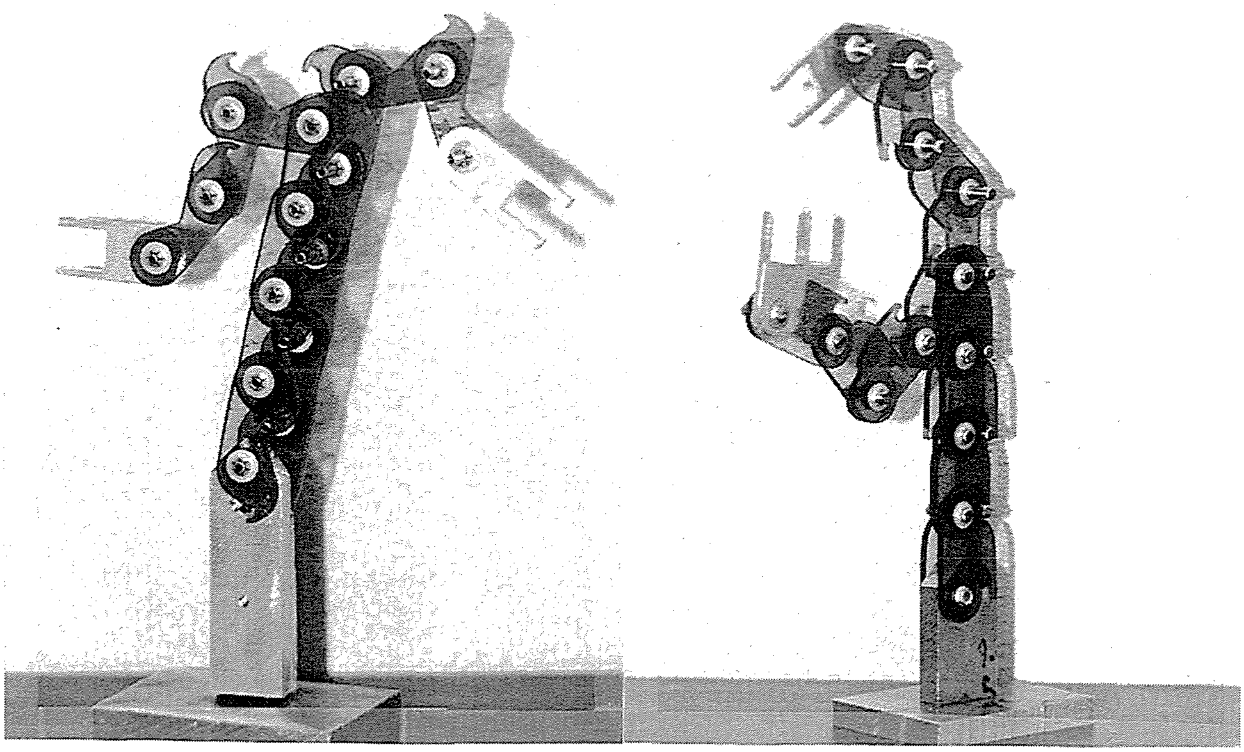


Figure 7. Simple prototypes of both models.

III. COOPERATIVE DUAL-ARM CAM-LOCK MANIPULATOR DYNAMICS

As discussed in the previous sections, the cooperative work of manipulators should offer some possibilities to solve more complex manipulation tasks. These tasks may only include and not be limited to the manipulation and transportation of heavy, long, large, or flexible objects [1]. Such applications generally imply that the kinematics configuration of both arms would vary during a working cycle. Furthermore, during all manipulation phases, the dynamical parameters (payload, moments of inertia, etc.) as well as the boundary conditions would also change. This implies that in order to obtain an accurate representation of the relative working regime, different mathematical models are required for dynamics description of each particular phase during the manipulation process [8-10]. Furthermore, during the design process, it is imperative that various mechanical configurations of the dual-arm manipulator are analyzed, and mathematical models of their dynamic behavior is available. This enables the robotics system to chose the appropriate manipulation mechanisms based on the adaptation criteria and the given constraints.

For the sake of analysis, let us start with considering a dual-arm cam-lock robotics system capable of manipulating an object in such a way that there is no relative motion among the grippers and the object. The goal is to carry out the kinematics and dynamics analysis of the cooperative task and to derive the corresponding equations of motion which may be used for future investigations and control laws.

For simplicity, let us further assume that both arms are open kinematics chains of rigid link, connected by a series of revolute joints, with each arm maintaining six degrees of freedom. Let us also assume that the object is a rigid body and the arms and the object are not subjected to external constraints of motion. In addition, it is noted that without loss of generality, the motion constraints imposed upon both manipulators by the cam-lock mechanism (which generally reduces their mobility) could also be incorporated. The cam-lock constraints are present when two or more joints are braced mechanically, forming a rigid structure (in the cam-locked portion of the arm) and the corresponding joints motions are halted by the arms control system (see Figure 8). The manipulator arms are denoted as the Left-Arm (LA) and the Right-Arm (RA), respectively.

In addition to the manipulator's parameters involved (partially shown in Figure 1), it is necessary to define the parameters that characterize the object, its position relative to the grippers, and the relative location of the manipulators. For this reason, three local reference coordinate frames are defined and shown in Figure 9. They are namely; $\mathbf{T}_L$, which is attached to the last link of the left-arm manipulator, $\mathbf{T}_R$, which is attached to the last link of the right-arm manipulator, and $\mathbf{T}_o$, which is attached to the object with it's origin at the center of mass, and it's axis along the object's principal axis of inertia. The following parameters are also defined:

$\mathbf{r}_R, \mathbf{r}_L$: relative position vectors defining frame $\mathbf{T}_o$ with respect to the local frames $\mathbf{T}_R$, and $\mathbf{T}_L$.

$\mathbf{A}_L^o, \mathbf{A}_R^o$: transformation matrix operators mapping vectors from frame $\mathbf{T}_o$ to frames $\mathbf{T}_R$, and $\mathbf{T}_L$.

ρ : position vector defining the base frame's origin of the right-arm relative to the base frame's origin of the left-arm.

$\mathbf{A}_L^R$: transformation matrix operator mapping vectors from the base frame of the right-arm manipulator to the base frame of the left-arm manipulator.

$\mathbf{m}_o$: mass of the object.

$\mathbf{I}_{xx}, \mathbf{I}_{yy}, \mathbf{I}_{zz}$: moments of inertia of the object in the coordinate frame $\mathbf{T}_o$.

Since the last links of the manipulator arms are rigidly connected to the object, the arms motions are no longer independent (see Figure 9). This implies that the overall degrees of freedom of the dual-arm robotics system has been reduced. Hence, one can readily determine the set of holonomic constraints imposed upon the motion of these manipulators.

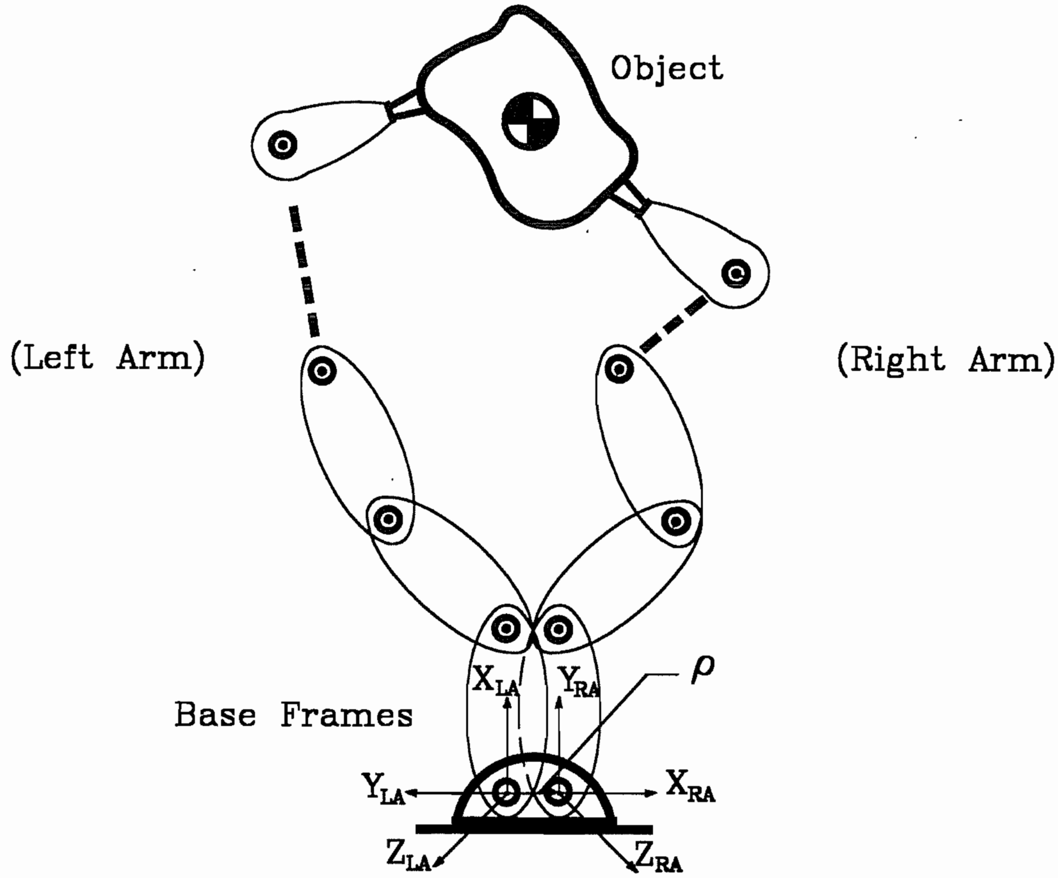


Figure 8. Relative location of dual-arm cam-lock manipulators.

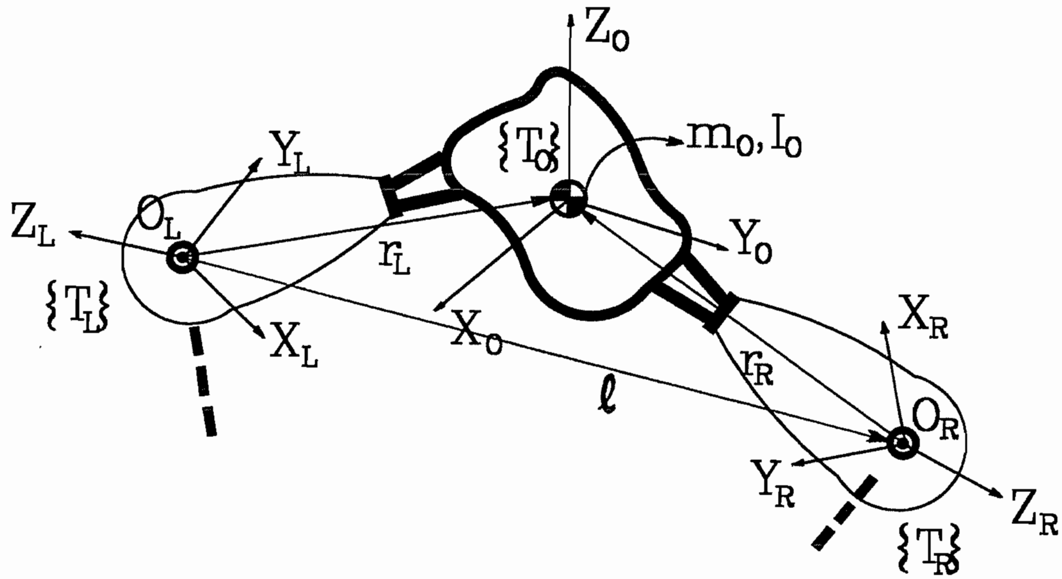


Figure 9. Relative location of the grippers and the object.

The most convenient form of kinematics relations among internal coordinates of manipulators are obtained when they are presented in terms of internal velocities, since they will appear in linear forms. The constraints are also treated in the mutually motionless local coordinate frames, $\mathbf{T}_L$, $\mathbf{T}_R$, and $\mathbf{T}_o$, where they would appear in the simplest form.

Using the above notations, components of an arbitrary vector $\mathbf{b}_L$, in frame $\mathbf{T}_L$, can be expressed by the components of the same vector in frame $\mathbf{T}_R$, as $\mathbf{b}_R$.

$$\mathbf{b}_L = \mathbf{A}^o_L \, (\mathbf{A}^o_R)^t \, \mathbf{b}_R \tag{2}$$

If $\mathbf{v}_L$ (i.e., $\mathbf{v}_R$) and ω_L (i.e., ω_R) denote the linear and angular velocity of the local coordinate frame $\mathbf{T}_L$ (i.e., $\mathbf{T}_R$), expressed in $\mathbf{T}_L$ (i.e., $\mathbf{T}_R$), we have:

$$\omega_L = \mathbf{A}^o_L \, (\mathbf{A}^o_R)^t \, \omega_R \tag{3}$$

and since the mutually motionless coordinate frames, $\mathbf{T}_R$, and $\mathbf{T}_L$ have the same angular velocity, we have:

$$\mathbf{v}_L = \mathbf{A}^o_L \, (\mathbf{A}^o_R)^t \, [\mathbf{v}_R + \ell \times \omega_R] \tag{4}$$

where; $\ell = \mathbf{A}^o_R(\mathbf{A}^o_L)^t \, \mathbf{r}_L - \mathbf{r}_R$ is the position vector locating $\mathbf{T}_R$ relative to $\mathbf{T}_L$. Replacing the cross product $\ell \times \omega_R$ with the corresponding matrix product $\mathbf{L}\,\omega_R$, where $\mathbf{L}$ is:

$$\mathbf{L} = \begin{bmatrix} 0 & -\ell_z & \ell_y \\ \ell_z & 0 & -\ell_x \\ -\ell_y & \ell_x & 0 \end{bmatrix} \tag{5}$$

Thus:

$$\begin{bmatrix} \mathbf{v}_L \\ \\ \omega_L \end{bmatrix} = \begin{bmatrix} \mathbf{A}^o_L \, (\mathbf{A}^o_R)^t & \mathbf{A}^o_L \, (\mathbf{A}^o_R)^t \, \mathbf{L} \\ \\ \mathbf{0}_3 & \mathbf{A}^o_L \, (\mathbf{A}^o_R)^t \end{bmatrix} \begin{bmatrix} \mathbf{v}_R \\ \\ \omega_R \end{bmatrix} \tag{6}$$

where $\mathbf{0}_3$ is a (3x3) null matrix. Let us now consider the Jacobians $\mathbf{J}_L$ and $\mathbf{J}_R$ of the left and the right arm, defined by:

$$\begin{bmatrix} \mathbf{v}_L \\ \\ \omega_L \end{bmatrix} = \mathbf{J}_L \, \dot{q}_L \tag{7}$$

$$\begin{bmatrix} \mathbf{v}_R \\ \\ \omega_R \end{bmatrix} = \mathbf{J}_R \, \dot{q}_R \tag{8}$$

where q_L and q_R are the vectors of joint variables of the left and the right-arms, respectively. These Jacobians are defined in the local coordinate frames, and act as operators that map vectors of joint velocities to velocities vectors in local coordinate systems. Combining equations (6), (7), and (8), results in the following equation which relates the joint velocities of both manipulators:

$$\mathbf{J}_L \dot{q}_L = \mathbf{Q}_L^R \mathbf{J}_R \dot{q}_R \tag{9}$$

where:
$$\mathbf{Q}_L^R = \begin{bmatrix} \mathbf{A}_L^o (\mathbf{A}_R^o)^t & \mathbf{A}_L^o (\mathbf{A}_R^o)^t \mathbf{L} \\ \mathbf{0}_3 & \mathbf{A}_L^o (\mathbf{A}_R^o)^t \end{bmatrix}$$

Differentiating equations (7) and (8) with respect to time results in the following equations, relating the joint accelerations to the manipulators tip accelerations in the local coordinate frames.

$$\begin{bmatrix} \mathbf{a}_L \\ \alpha_L \end{bmatrix} = \mathbf{J}_L \ddot{q}_L + f_L(q_L, \dot{q}_L) \tag{10}$$

$$\begin{bmatrix} \mathbf{a}_R \\ \alpha_R \end{bmatrix} = \mathbf{J}_R \ddot{q}_R + f_R(q_R, \dot{q}_R) \tag{11}$$

where $f_L(q_L, \dot{q}_L)$ and $f_R(q_R, \dot{q}_R)$ denote $\dot{\mathbf{J}}_L \dot{q}_L$ and $\dot{\mathbf{J}}_R \dot{q}_R$, respectively.

And, differentiating equation (9) with respect to time results in an equation which relates the joint accelerations of both manipulators.

$$\mathbf{J}_L \ddot{q}_L + f_L(q_L, \dot{q}_L) = \mathbf{Q}_L^R [\mathbf{J}_R \ddot{q}_R + f_R(q_R, \dot{q}_R)] \tag{12}$$

Let us now define $\mathbf{K}_1$, and $\mathbf{K}_2$ as:

$$\mathbf{K}_1(q_L, q_R) = (\mathbf{J}_R)^{-1} (\mathbf{Q}_L^R)^{-1} \mathbf{J}_L$$

$$\mathbf{K}_2(q_L, \dot{q}_L, q_R, \dot{q}_R) = (\mathbf{J}_R)^{-1} [(\mathbf{Q}_L^R)^{-1} f_L - f_R]$$

Hence, we can express equations (9) and (12) in a simpler form as:

$$\dot{q}_R = \mathbf{K}_1 \dot{q}_L \qquad (13)$$

and,

$$\ddot{q}_R = \mathbf{K}_1 \ddot{q}_L + \mathbf{K}_2 \qquad (14)$$

Note that $\mathbf{K}_1$ acts like an operator that maps joint velocities of the left arm to the joint velocities of the right arm. Since there are exactly six independent holonomic constraints among joint velocities of the arms, expressed in the form of equation (13), it follows that there is a loss of six degrees of freedom. Therefore:

[(D.O.F. of the Left-Arm) + (D.O.F. of the Right-Arm)] - (Number of Holonomic Constraints) = Overall D.O.F. of the Robotics System (15)

Therefore, in our example we have: [(6) + (6)] - (6) = 6 D.O.F. However, we could have come to the same conclusion by observing the fact that when the motion of one arm is given, the motion of the second arm is also defined, and the inverse kinematics uniquely determines its motion in the respective joint coordinates. Thus, a set of six independent variables serving as the generalized coordinates must be chosen, in order to describe the dynamic behavior of the system. Let this set to be the set of joint coordinates of the left-arm, such that the rest of equations are reduced and mapped to the joint space of the left arm. In other words, when the joint coordinates (i.e. velocities, and accelerations) of the left arm are known, joint coordinates of the right-arm can be computed by the constraint relations. Equation (15) could be readily modified for the case where some of the links in the dual arm robotics system are cam-locked from the base, adding additional constraints to the system such that:

[(D.O.F. of the L.A.) + (D.O.F. of the R.A.)] - [(Number of Holonomic Constraints) + 2 $\times$ (Number of Cam-Locked Links)] = Overall D.O.F. of the Robotics System (16)

Let us now consider the motion of the object being held by the dual-arm manipulator as shown in Figure 10. To perform this study, the following notations are defined:

- ($\mathbf{F}_L$, $\mathbf{F}_R$, $\mathbf{M}_L$, $\mathbf{M}_R$) : forces and moments applied on the object by the arms, given in coordinate frames $\mathbf{T}_L$, and $\mathbf{T}_R$.
- $\mathbf{F}_{Le}$, $\mathbf{F}_{Re}$: the (6 x 1) generalized force/moment vectors at the end-effector.

a_o, α_o, ω_o : linear and angular acceleration, and angular velocity vectors of the object in coordinate frame $\mathbf{T}_O$, respectively.

$\mathbf{I}_O$: inertia tensor of the object in coordinate frame $\mathbf{T}_O$.

$\mathbf{A}_B^L(q_L)$: transformation matrix relating coordinate frame $\mathbf{T}_L$ to the absolute base frame of the left-arm (LA).

$\mathbf{g}$: gravitational acceleration vector in the absolute coordinate frame.

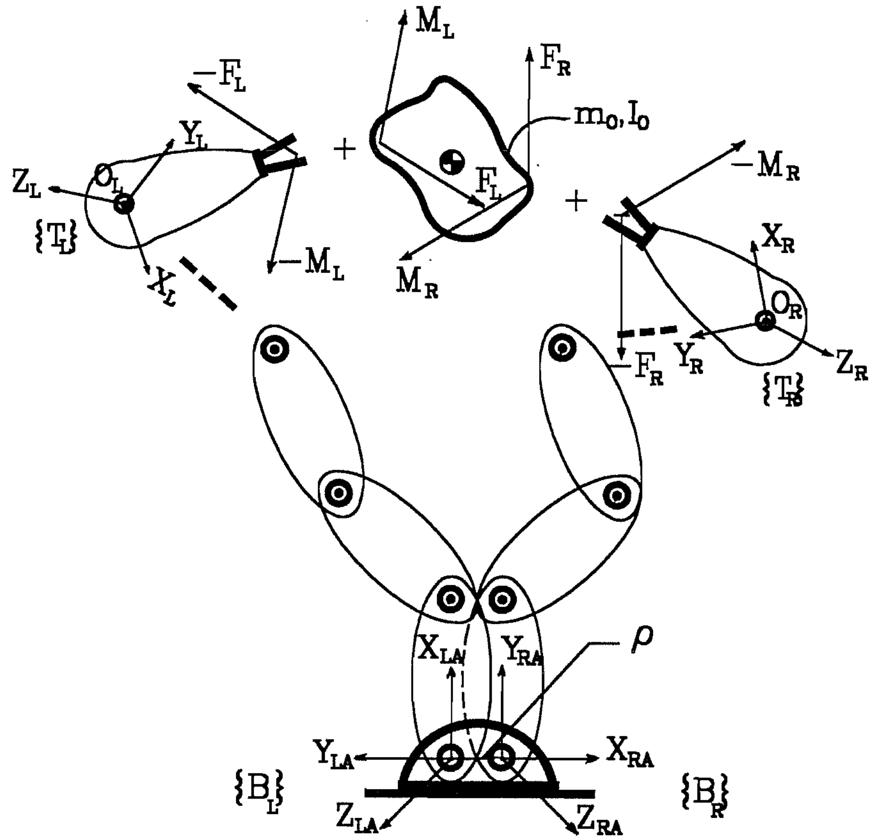


Figure 10. Object's motion due to forces and moments applied by the arms.

Applying force balance on the object in the coordinate frame $\mathbf{T}_L$, we have:

$$\mathbf{F}_L + \mathbf{A}_L^o (\mathbf{A}_R^o)^t \mathbf{F}_R = \mathbf{m}_O \mathbf{A}_L^o a_o - \mathbf{m}_O (\mathbf{A}_B^L)^t \mathbf{g} \tag{17}$$

where:

$$\mathbf{A}_L^o a_o = \mathbf{a}_L + \alpha_L \times \mathbf{r}_L + \omega_L \times (\omega_L \times \mathbf{r}_L) \tag{18}$$

Hence,

$$\mathbf{F}_L + \mathbf{A}_L^o (\mathbf{A}_R^o)^t \mathbf{F}_R = \mathbf{m}_O [\mathbf{a}_L + \alpha_L \times \mathbf{r}_L + \omega_L \times (\omega_L \times \mathbf{r}_L)] - \mathbf{m}_O (\mathbf{A}_B^L)^t \mathbf{g} \tag{19}$$

Furthermore, applying moment balance on the object with respect to the origin of the frame $\mathbf{T}_o$, in the coordinate system $\mathbf{T}_L$, we have:

$$\mathbf{M}_L - \mathbf{r}_L \times \mathbf{F}_L + \mathbf{A}_L^o (\mathbf{A}_R^o)^t (\mathbf{M}_R - \mathbf{r}_R \times \mathbf{F}_R) = \mathbf{A}_L^o [\mathbf{I}_o \alpha_o - (\mathbf{I}_o \omega_o) \times \omega_o] \tag{20}$$

mapping α_o and ω_o in frame $\mathbf{T}_L$, results in:

$$\mathbf{M}_L - \mathbf{r}_L \times \mathbf{F}_L + \mathbf{A}_L^o (\mathbf{A}_R^o)^t (\mathbf{M}_R - \mathbf{r}_R \times \mathbf{F}_R) = \mathbf{A}_L^o \mathbf{I}_o (\mathbf{A}_L^o)^t \alpha_L - [\mathbf{A}_L^o \mathbf{I}_o (\mathbf{A}_L^o)^t \omega_L] \times [(\mathbf{A}_L^o)^t \omega_L] \tag{21}$$

Since $\mathbf{A}_L^o$ is a unitary matrix, and $\mathbf{I}_o$ is a diagonal matrix, one can readily show that: $\mathbf{A}_L^o \mathbf{I}_o (\mathbf{A}_L^o)^t = \mathbf{I}_o$. Considering the following notations:

$$\mathbf{a}_1(\dot{q}_L) = \omega_L \times (\omega_L \times \mathbf{r}_L) \tag{22}$$

$$\mathbf{a}_2(\dot{q}_L) = (\mathbf{I}_o \omega_o) \times [(\mathbf{A}_L^o)^t \omega_L] \tag{23}$$

and, instead of the vector cross product, introducing matrix products such that:

$$\mathbf{r}_L \times \mathbf{F}_L \Leftrightarrow \mathbf{S}_L . \mathbf{F}_L \qquad \Rightarrow \mathbf{S}_L = \begin{bmatrix} 0 & -r_{lz} & r_{ly} \\ r_{lz} & 0 & -r_{lx} \\ -r_{ly} & r_{lx} & 0 \end{bmatrix} \tag{24}$$

and,

$$\mathbf{r}_R \times \mathbf{F}_R \Leftrightarrow \mathbf{S}_R . \mathbf{F}_R \qquad \Rightarrow \mathbf{S}_R = \begin{bmatrix} 0 & -r_{rz} & r_{ry} \\ r_{rz} & 0 & -r_{rx} \\ -r_{ry} & r_{rx} & 0 \end{bmatrix} \tag{25}$$

As a result, the force and moment balance equations (19) and (21) can be presented in a compact form:

$$\mathbf{F}_L + \mathbf{A}_L^o (\mathbf{A}_R^o)^t \mathbf{F}_R = \mathbf{m}_o [\mathbf{a}_L - \mathbf{S}_L \alpha_L + \mathbf{a}_1] - \mathbf{m}_o (\mathbf{A}_B^L)^t \mathbf{g} \tag{26}$$

$$\mathbf{M}_L - \mathbf{S}_L \mathbf{F}_L + \mathbf{A}_L^o (\mathbf{A}_R^o)^t (\mathbf{M}_R - \mathbf{S}_R \mathbf{F}_R) = \mathbf{I}_o \alpha_L - \mathbf{a}_2 \tag{27}$$

Let us further define the following notations:

$$\mathbf{A} = \begin{bmatrix} \mathbf{I}_3 & \mathbf{0}_3 \\ -\mathbf{S}_L & \mathbf{I}_3 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} \mathbf{A}_L^o (\mathbf{A}_R^o)^t & \mathbf{0}_3 \\ -\mathbf{A}_L^o (\mathbf{A}_R^o)^t \mathbf{S}_R & \mathbf{A}_L^o (\mathbf{A}_R^o)^t \end{bmatrix},$$

$$\mathbf{C} = \begin{bmatrix} \mathbf{m}_o\mathbf{I}_3 & -\mathbf{m}_o\mathbf{S}_L \\ \mathbf{0}_3 & \mathbf{I}_o \end{bmatrix} \mathrm{J}_L(q_L), \quad \mathbf{D} = \begin{bmatrix} \mathbf{m}_o\mathbf{I}_3 & -\mathbf{m}_o\mathbf{S}_L \\ \mathbf{0}_3 & \mathbf{I}_o \end{bmatrix} f_L(q_L, \dot{q}_L) - \begin{bmatrix} \mathbf{m}_o(\mathbf{A}_B^L)^t\mathbf{g} - \mathbf{m}_o\, \mathbf{a}_1 \\ \mathbf{a}_2 \end{bmatrix}$$

$$\mathbf{F}_{Le} = \begin{bmatrix} \mathbf{F}_L \\ \mathbf{M}_L \end{bmatrix}, \quad \mathbf{F}_{Re} = \begin{bmatrix} \mathbf{F}_R \\ \mathbf{M}_R \end{bmatrix}, \text{ and } \mathbf{F}_e = \begin{bmatrix} \mathbf{F}_{Le} \\ \mathbf{F}_{Re} \end{bmatrix}.$$

where $\mathbf{I}_3$ denotes a third order identity matrix. Considering equations (10) and (11) in conjunction with equations (26) and (27), the differential equations of motion of the object can be unified and presented in the matrix form as:

$$\mathbf{AF}_{Le} + \mathbf{BF}_{Re} = \mathbf{C}\ddot{q}_L + \mathbf{D} \tag{28}$$

Extending the conventional dynamic model of each manipulator arm [8-10] to include the effects of external forces and torques, $\mathbf{F}_e$, exerted at the manipulator's tip, we obtain:

$$\mathbf{M}(q)\ddot{q} + \mathbf{V}(q, \dot{q}) + \mathbf{G}(q) = \tau + \tau_e \tag{29}$$

where $\mathbf{M}(q)$ is the manipulator's mass matrix, $\mathbf{V}(q, \dot{q})$ is the vector of centrifugal and Coriollis terms, $\mathbf{G}(q)$ is the vector of gravity terms, τ is the vector of joint forces/torques, and τ_e is the effect of external forces/torques vector, $\mathbf{F}_e$, as seen from the joint space of the manipulator. The relationship between the τ_e and $\mathbf{F}_e$ can be obtained by the principle of virtual work. Thus, let δr represent the infinitesimal displacement of the manipulator's tip in the end-effector coordinate frame, and $\mathbf{F}_e$ be the external force/torque vector defined in the same frame. Neglecting inertial effects and frictions at the joints, we could write the following relation for the virtual work:

$$\delta \mathbf{W} = (\tau_e)^t.\delta q - (\mathbf{F}_e)^t.\delta r = (\tau_e - \mathbf{J}^t.\mathbf{F}_e)^t \delta q \tag{30}$$

Since δq represents linearly independent admissible displacements, for $\delta \mathbf{W}$ to vanish, the term (τ_e - $\mathbf{J}^t.\mathbf{F}_e$) must be equal to zero. Hence:

$$\tau_e = \mathbf{J}^t.\mathbf{F}_e \tag{31}$$

Therefore, the dynamics model of each manipulator arm in the space of its generalized coordinates becomes:

$$\mathbf{M}(q)\ddot{q} + \mathbf{V}(q, \dot{q}) + \mathbf{G}(q) = \tau + \mathbf{J}^t.\mathbf{F}_e \tag{32}$$

Finally in order to obtain the cooperative dynamic model of the dual-arm robotics system, one should unify the dynamic equations of the manipulators (32) with the equation of motion of the object (28), by eliminating the forces of interaction ($\mathbf{F}_{Le}$ and $\mathbf{F}_{Re}$) from these models. Dynamic equations representing the left-arm and the right-arm are:

$$\mathbf{M}_L(q_L)\ddot{q}_L + \mathbf{V}_L(q_L, \dot{q}_L) + \mathbf{G}_L(q_L) = \tau_L - \mathbf{J}_L{}^t(q_L).\mathbf{F}_{Le} \tag{33}$$

$$\mathbf{M}_R(q_R)\ddot{q}_R + \mathbf{V}_R(q_R, \dot{q}_R) + \mathbf{G}_R(q_R) = \tau_R - \mathbf{J}_R{}^t(q_R).\mathbf{F}_{Re} \tag{34}$$

Negative sign appearing in the external force/torque term stems from the convention adapted in Figure 4. Evaluating $\mathbf{F}_{Le}$ from equation (28) and substituting it in equation (33) results:

$$[\mathbf{M}_L + \mathbf{J}_L{}^t\mathbf{A}^{-1}\mathbf{C}]\,\ddot{q}_L + \mathbf{V}_L + \mathbf{G}_L + \mathbf{J}_L{}^t\mathbf{A}^{-1}\mathbf{D} = \tau_L + \mathbf{J}_L{}^t\mathbf{A}^{-1}\mathbf{B}\mathbf{F}_{Re} \tag{35}$$

Evaluating $\mathbf{F}_{Re}$ from equation (34), and replacing $\ddot{q}_R$ using equation (14), we have:

$$\mathbf{F}_{Re} = -(\mathbf{J}_R{}^t)^{-1}[\mathbf{M}_R[\mathbf{K}_1\ddot{q}_L + \mathbf{K}_2] + \mathbf{V}_R + \mathbf{G}_R - \tau_R] \tag{36}$$

Substituting equation (36) into the equation (35), and rearranging the terms, results in:

$$[\mathbf{M}_L + \mathbf{J}_L{}^t\mathbf{A}^{-1}\mathbf{B}(\mathbf{J}_R{}^t)^{-1}\mathbf{M}_R\mathbf{K}_1 + \mathbf{J}_L{}^t\mathbf{A}^{-1}\mathbf{C}]\,\ddot{q}_L + \mathbf{V}_L + \mathbf{J}_L{}^t\mathbf{A}^{-1}\mathbf{D} +$$

$$+ \mathbf{J}_L{}^t\mathbf{A}^{-1}\mathbf{B}(\mathbf{J}_R{}^t)^{-1}[\mathbf{M}_R\mathbf{K}_2 + \mathbf{V}_R + \mathbf{G}_R] = \tau_L + \mathbf{J}_L{}^t\mathbf{A}^{-1}\mathbf{B}(\mathbf{J}_R{}^t)^{-1}\tau_R \tag{37}$$

For the sake of clarity, let us define the following terms:

$$\Phi(q_L, q_R) = \mathbf{J}_L{}^t\mathbf{A}^{-1}\mathbf{B}(\mathbf{J}_R{}^t)^{-1}$$

$$\Psi(q_L, q_R) = \mathbf{M}_L + \Phi\mathbf{M}_R\mathbf{K}_1 + \mathbf{J}_L{}^t\mathbf{A}^{-1}\mathbf{C}$$

$$\Gamma(q_L, q_R, \dot{q}_L, \dot{q}_R) = \mathbf{V}_L + \mathbf{J}_L{}^t\mathbf{A}^{-1}\mathbf{D} + \Phi[\mathbf{M}_R\mathbf{K}_2 + \mathbf{V}_R + \mathbf{G}_R]$$

Then, using these notations, equation (37) representing the dynamics model of the cooperative task of a dual-arm cam-lock manipulator takes the following form:

$$\Psi(q_L, q_R)\ddot{q}_L + \Gamma(q_L, q_R, \dot{q}_L, \dot{q}_R) = \tau_L + \Phi(q_L, q_R)\tau_R \quad (38)$$

V. CONCLUSIONS

Preliminary design features and the cooperative dynamics modeling of a new class of robotics structure named as the Dual-Arm Cam-Lock Manipulator has been presented. The cam-lock mechanism at two different locations along the links were studied. The cam-lock location may be optimized along the link for various designs and performance. Furthermore, a mobility analysis of this type of manipulator was performed and the motion constraints were identified. Further research on the design, kinematics, and dynamics issues of this type of manipulator is presently underway and will be reported in a following paper.

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Dr. Ali Meghdari
AHMCT Center
University of California, Davis
Department of Mechanical, Aeronautical and Materials Engineering
Davis, CA 95616

Dear Dr. Meghdari:

I am pleased to inform you that the Program Committee has accepted your paper, #0008 :

The Cooperative Dual-Arm Cam-Lock Manipulator

for presentation at the 1994 IEEE International Conference on Robotics and Automation.

In the next few days, you will receiving an author's kit directly from the Computer Society Press. Please note that the final camera copy of the paper, incorporating any recommendations by the reviewers, must be returned to them no later than **February 15, 1994**. This is a strict deadline. Papers received after that date will not appear in the Proceedings. Each paper is limited to 6 pages. Two additional pages are allowed, provided that a payment of $150 per additional page is enclosed with the manuscript. Papers exceeding 8 pages will not be published.

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New York State Center for Advanced Technology in Automation and Robotics
Rensselaer Polytechnic Institute
Troy, New York 12180-3590, U.S.A.

I look forward to seeing you in San Diego.

Cordially,

Harry E. Stephanou
Program Chairman

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OFFICE OF TECHNOLOGY TRANSFER
1320 Harbor Bay Parkway, Suite 150
Alameda, CA 94502
tel: (510) 748-6600
fax: (510) 748-6639

November 9, 1993

Dr. Ali Meghdari
Mechanical & Aeronautical Eng.
AHMCT Center, Rm 1009 Academic Surge
University of California
Davis, CA 95616

Re: **THE DUAL-ARM CAM-LOCK ROBOT MANIPULATOR**
UC Case No.: 93-353-1

Dear Dr. Meghdari:

This letter acknowledges receipt of your formal written disclosure and record of invention. A permanent file has been established as our official record, and will be referred to by the UC Case number shown above.

Your disclosure has been assigned to Kathy S. Willis, who will be completing a review of patentability and a licensing assessment and will call you to discuss your invention and its potential uses.

This disclosure will be governed by the UC Patent Policy at the time of the disclosure.

If you have any further questions, please do not hesitate to call us at (510) 748-6600.

Sincerely,

Linda S. Stevenson
Prosecution Analyst

LSS:rlv

cc: Nora Hackett, Ph.D., TLO, UCD

DISCLOSURE AND RECORD OF INVENTION FORM

Note: When completed, the *Disclosure and Record of Invention Form* in an important legal document. Care should be taken in its preparation. Please refer to accompanying instructions. If you desire assistance, call the Office of Technology Transfer (University Patent Office) at (510) 748-6600. Information contained in this document is maintained in confidence by the University Patent Office and normally will not be released to others except with attorney-client privilege, to research sponsors as required by contract, or under appropriate secrecy agrements, until a patent application is filed, the information is published, a determination not to file a patent application is made, or as may be required by law. The information contained should not be disclosed to others outside the University, except as described in section 9, without the approval of the University Office of Technology Transfer. It is *not* the practice of the University Office of Technology Transfer to send your Record of Invention to other University employees for peer review.

1. Short descriptive title of the invention.

THE DUAL-ARM CAM-LOCK ROBOT MANIPULATOR

2. A. Briefly summarize the invention here. Include the novel features and advantages.

Dual-Arm Cam-Lock Manipulator is composed of two multi-degree of freedom planar arms. It is designed to be capable of performing a wide variety of tasks by automatically reconfiguring itself to form a variable geometry, stiffness, and workspace robotic structure. It is able to form a stronger manipulator with variable rigidity/geometry by the virtue of a passive Cam-Lock Mechanism incorporated within the design of each arm. The trick lies in the geometrical design of the arm's joints and linkages. Due

B. Detailed description of the invention using additional sheets as necessary and attach as appendix.

to the existing similarities in the geometry of the designed linkages with those of the cam mechanisms, the term Cam-Lock was chosen to describe it. Due to its light weight design and geometry, it can be folded in a controlled manner to a compact form, making it portable, or to be used as a deployable robotics structure. (Details encl

3. List the funding source(s) for the project under which this invention was made. If applicable, identify by contract or grant number and name the Principal Investigator/Supervisor of each.

Funding Source/Sponsor	Contract or Grant Number	Principal Investigator/ Supervisor
~~AHMCT Research Program (CalTrans), Partial Support:~~	~~183J~~	~~Bahram Ravani, Ph.D.~~
~~Sharif University of Technology~~ , ~~Partial Support~~		~~Ali Meghdari, Ph.D.~~

4. For any "Inventor" named (item 13) who is not employed full-time by the University of California, please identify other employers (e.g., Veterans Administration, Howard Hughes Medical Institute, USDA), the percent of salary time funded by such other employer, and the nature of the other employment (such as research, teaching or clinical duties).

Associate Professor of Mechanical Engineering (on sabbatical leave since March, 1993)

Department of Mechanical Engineering

Sharif University of Technology, Tehran, Iran.

5. When did you first conceive this invention?

April, 1993

6. What is the date of the first written record (notebook, letter, proposal, drawing, etc.) of this invention? Identify the document, page numbers involved, and location of the document.

June 1993, prepared an abstract of a paper describing the idea and submitted it for review to the 1994 ASCE SPACE Conference on"Robotics for Challenging Environments".

7. When did you first successfully test this invention? June-1993.

8. If you have disclosed this invention to non-UC personnel (including research sponsor) then indicate when, under what circmstances, and to whom.

a. orally To: Professor M. Shahinpoor of the Univ. of New Mexico(Sept. 18, 1993), and Dr. H. Seraji of NASA-JPL (October,5, 1993), and discussed with them its features and characteristics.

b. in writing
To the Office of Scientific Research, Sharif University of Technology, Tehran, Iran. In the form of a sabbatical report to home institution, since I am required to report my research activities during the sabbatical period inorder to receive continued funding

c. by actual use, demonstration, or posters
None

9. Have you submitted or do you plan to submit a report, abstract, paper or thesis relating to this invention for publication, for presentation at a conference, or to a research sponsor? YES.

If yes, give details, including the actual or planned date of submission. If a manuscript has been accepted, give the anticipated publication date. Append a copy of the latest draft manuscript available. (See instructions for the effect of publication prior to the filing of a patent application.)

Full paper on the subject is accepted for presentation & publication at the 1994 ASCE SPACE Conference on "Robotics for Challenging Environments".(to be published Feb.,1994). Also, a complted version of the paper is submitted to the 1994 IEEE Conf. on Robotics &

10. Identify any references, patent applications, or other publications of which you are aware and which you believe to be pertinent to this invention. Please attach a copy of each of these references, if available.

Design idea were simply obtained from personal experience with chain-like manipulator arms, and the idea of developing mechanical coordination among two arms in order to form a variable strength/geometry manipulator, when neccessary.(the concept of unity is also applied).

11. If any proprietary material (e.g., cell line, antibody, plasmid, computer software, or chemical compound) obtained from outside your laboratory was used to develop this invention under a restrictive written or oral transfer agreement (other than a normal purchasing agreement), please attach a copy or summary of that agreement.

None.

12. List companies you believe might be interested in using, developing or marketing this invention.

Schilling Robotics Development, NASA-JPL Telerobotics Lab., CalTrans, Unimation Inc., Toshiba, ADEPT Technologies, and Many Robot Manufacturers.

13. Signatures, Names and Addresses of Inventors

a)		b)	
Signature: [signature]	Date: Oct. 26, 93	Signature:	Date:
Print Name: ALI MEGHDARI	Oct. 25, 1993	Print Name: ---------------	
Dept/ORU: Mechanical & Aeronautical Engineering		Dept/ORU: -------------	
Rm & Bldg: AHMCT Center, Rm 1009 Academic Surge		Rm & Bldg: -------------	
Campus (Address if non-UC): Univ. of Calif.-Davis		Campus (Address if non-UC): ----------	
City/State/Zip: Davis, CA. 95616		City/State/Zip:	
Telephone: (916) 752-6366		Telephone:	

Note: If there are more inventors please provide signatures, names and addresses on an additional sheet of paper.

14. Technically Qualified Witnesses (Two Required)—invention disclosed to and understood by:

a) Dr. Bahram Ravani (U.C.-Davis)
Signature: Bahram Ravani Date: 10-28-93
Print Name

b) Dr. Steven A. Velinsky (U.C.-Davis)
Signature: [signature] Date: 10/29/93
Print Name

Submit this form with ORIGINAL SIGNATURES directly to:
Director—Office of Technology Transfer
Office of the President
University of California
1320 Harbor Bay Parkway, Suite 150
Alameda, CA 94501

If you do not receive an acknowledgement within 30 days, please call the University Office of Technology Transfer at (510) 748-6600.

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Effective 1/1/82
Revised 2/93

Retention: 7 yrs. after last patent expires or 10 yrs. after the date of the last action whichever is later

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J.W. PELTASON
President

V. WAYNE KENNEDY
Senior Vice President—
Business & Finance

OFFICE OF TECHNOLOGY TRANSFER
1320 Harbor Bay Parkway, Suite 150
Alameda, CA 94502
tel: (510) 748-6600
fax: (510) 748-6639

November 24, 1993

Mr. Thomas West
Office of Technology and Research
5900 Folsom Blvd.
P. O. Box 19128
Sacramento, CA 95819

Re: **THE DUAL-ARM CAM-LOCK ROBOT MANIPULATOR**
UC Case No.: 93-353-1

Dear Mr. West:

Please find enclosed a copy of the confidential disclosure that appears to have been developed in part under research funded by the California Department of Transportation.

Our office is currently reviewing this disclosure for patentability and licensing potential. We will advise you as soon as we determine whether we wish to retain title under Public Law 98.620.

Sincerely,

Linda S Stevenson

Linda S. Stevenson
Prosecution Analyst

LSS:rlv

Enclosure

cc: Dr. Ali Meghdari
Nora Hackett, Ph.D., TLO, UCD

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OFFICE OF TECHNOLOGY TRANSFER
1320 Harbor Bay Parkway, Suite 150
Alameda, CA 94502
tel: (510) 748-6600
fax: (510) 748-6639
kathy@ott.ucop.edu
January 4, 1994

Mr. John R. White, President
REMOTEC, Inc.
114 Union Valley Road
Oak Ridge, TN 37830
(615) 483-0228

Re: **UC Case No. 93-353-1: Variable Robot Manipulator**

Dear Mr. White:

Thank you for your interest in the University and the products of its research. Before I can send you any proprietary information about the invention referenced above, I must have a fully-executed Non-Disclosure Agreement on file.

I am enclosing two originals of our standard Non-Disclosure Agreement for the subject invention. Please have both originals of the Agreement signed by an officer of **REMOTEC, Inc.** and return both to me. I will have the Agreement executed on behalf of The Regents and return one fully-executed original of the Agreement to you.

Upon execution of the Agreement by both parties, I will send you a copy of the invention disclosure and other pertinent information. I will also advise our inventor that he is free to provide you with any information which may be required for the commercial evaluation of the invention.

Again, thank you for your interest. I am looking forward to working with you.

Sincerely,

Kathy S. Willis

Kathy S. Willis
Licensing Associate

KSW:ewk
Enclosures

bcc: Dr. Ali Meghdari
Dr. Nora Hackett, Office of Research, UCD

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OFFICE OF TECHNOLOGY TRANSFER
1320 Harbor Bay Parkway, Suite 150
Alameda, CA 94502
tel: (510) 748-6600
fax: (510) 748-6639
kathy@ott.ucop.edu

January 14, 1994

Mr. John R. White, President
REMOTEC, Inc.
114 Union Valley Road
Oak Ridge, TN 37830
(615) 483-0228

Re: <u>UC Case No. 93-353-1: Variable Robot Manipulator</u>

Dear Mr. White:

Enclosed is an original, fully-executed Non-Disclosure Agreement covering the invention referenced above. Also enclosed are copies of the invention disclosure and related material. The disclosure, marked "PROPRIETARY INFORMATION," is to be treated according to the terms of the Agreement.

By copy of this letter, I am informing our inventor, Dr. Ali Meghdari, that he may provide your company with any information which may be required for the commercial evaluation of the invention. He can be reached at the following address:

Dr. Ali Meghdari
Mechanical & Aeronautical Engineering
AHMCT Center, Room 1009 Academic Surge
University of California
Davis, CA 95616
Tel: (916) 752-6366
Fax: (916) 752-6714

I encourage you to contact Dr. Meghdari.

Please note that we may offer this technology to other companies during the period of your commercial evaluation.

Sincerely,

Kathy S. Willis
Licensing Associate

KSW:ewk
Enclosures

cc: Dr. Ali Meghdari
Nora Hackett, Ph.D., TLO, UCD