

# BINARY HYPER-REDUNDANT ROBOTIC MANIPULATOR CONCEPT

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## ABSTRACT

*Continuously actuated robotic manipulators are the most common type of manipulators even though they require sophisticated and expensive control and sensor systems to function with high accuracy and repeatability. Binary hyper-redundant (Bi-HR) robotic manipulators are potential candidates to be used in applications where high repeatability and reasonable accuracy are required. Such applications include pick-and-place, spot welding and assistants to people with disabilities. Generally, the Bi-HR manipulator is relatively inexpensive, lightweight, and has a high payload to arm weight ratio. This paper discusses a concept of Bi-HR manipulator, influencing concepts to the Bi-HR, examples of applications, and its advantages and disadvantages.*

## 1. INTRODUCTION

Continuously actuated robotic manipulators are the most common type of manipulators even though they require sophisticated and expensive control and sensor systems to function with high accuracy and repeatability. Binary hyper-redundant (Bi-HR) robotic manipulators are potential candidates to be used in applications where high repeatability and reasonable accuracy are required. Such applications include pick-and-place, spot welding and assistants to people with disabilities.

In this study the Bi-HR robotic manipulator is macroscopically serial in structure, meaning that the overall structure is a serial cascade of units with each unit having either a serial or parallel kinematic structure. Moreover, this Bi-HR manipulator has binary states, and is a sensorless system, which means the manipulator requires no feedback control. Therefore, the manipulator has a very simple computer interface. In general, the Bi-HR manipulator is relatively inexpensive, lightweight, and has a high payload to arm weight ratio. However, there are some drawbacks of this manipulator type (e.g., its non-continuous (discrete) workspace, the large amount of calculations required for inverse kinematics, etc.)

This paper discusses: a concept of Bi-HR robotic manipulators in Section 2, Sections 3 and 4 review influencing concepts of Bi-HR robotic manipulator, such as, adaptive structures, sensorless systems, and hyper-redundant robots. Section 5

presents the past efforts of this type of manipulator, while Section 6 lists advantages, disadvantages, and example applications of the manipulators. Finally, Section 7 summaries the paper.

## 2. CONCEPTS OF THE BI-HR ROBOTIC MANIPULATOR

The binary hyper redundant (Bi-HR) robotic manipulator is influenced by several successive concepts, such as, the concepts of adaptive structures, sensorless systems, and hyper-redundant robotic manipulators. In this study, the Bi-HR consists of several 3-bit planar variable geometry truss (VGT) modules stacked next to each other to form a chain or snake-like manipulator. The novelty of this planar hyper-redundant arm is that it uses a binary actuator in each leg of the VGT. Thus, each module has a total of 8 ( $=2^3$ ) possible configurations. Figure 1 illustrates 8-possible configurations. The number of reachable points of the manipulator is exponential in the number of actuators. For example, a manipulator consists ten 3-bit-VGT modules can reach total of  $2^{3 \times 10}$  ( $= 1.07$  Billion) different positions. If there were enough modules stacked next to each other, the discrete manipulator workspace would become almost similar to the continuous workspace of traditional continuously actuated robots. (In section 5, Bi-HR robotic manipulators are discussed and illustrated.)

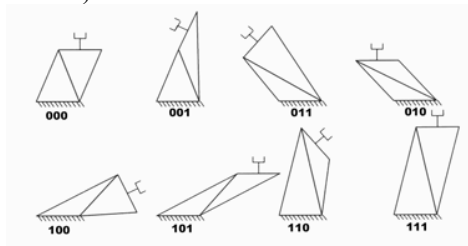


Figure 1: 8-possible configuration of a 3-Bit Planar VGT.

However, the inverse kinematics of binary or discretely-actuated hyper-redundant manipulators with a large number of actuators becomes impossibly complex when searching using direct-forward kinematics. This issue led Chirikjian and his co-workers including the author, to explore a number of statistical inverse kinematics algorithms for this type of manipulator.

### 3. ADAPTIVE STRUCTURES AND SENSORLESS SYSTEM

In this section, the two concepts which influenced two important features of the Bi-HR manipulator in this study are discussed. An adaptive structure is defined as a system with structural and geometric characteristics that are suitable to meet given tasks or requirements. In the literature, this type of structure is called by various names, such as smart structures, variable structures, etc.

Originally, adaptive structures were developed primarily for space missions. In 1990, Wada [1] discussed an overview of adaptive structures, included several different types of adaptive structures, etc. The type of adaptive structure that played a role in influencing the design of the Bi-HR manipulator in this concept is the variable geometry truss (VGT). In the 1980's the VGT became a source of interest to many in the field of robotics. This led Miura and Furuya [2] in Japan and Rhodes and Mikulas [3] in the U.S.A. to explore new possibilities of adaptive structures.

A number of researchers studied VGT manipulators, and compared them to traditional types of robotic manipulators. Hughes *et al.* [4] compares a VGT manipulator to "the Canadarm" in weight, storage volume, degree of freedom, maximum tip load, etc. Results show that at the same arm weight, the truss-type manipulator can hold up to 6-times more weight than the traditional type of manipulator. (Note that "Canadarm" is the shuttle manipulator developed in Canada, and currently used on NASA space shuttles).

The kinematics, dynamics, and vibrations of VGT manipulator have become important research topics. Robertshaw and Reinholtz [5] presented an analysis of vibrations in VGTs. A prototype of a twenty-one degree of freedom truss has been designed and assembled. In the early 1990's, Naccarato and Hughes [6] discussed an early version of inverse kinematic analysis of VGT manipulators. Then, Chirikjian and his co-workers (e.g., [7-11]) presented a number of kinematic analyses, and trajectory planning which they were able to apply to the VGT manipulator.

The second concept was the sensorless system. This concept was discussed by a number of researchers. Erdmann and Mason [12] explored a study of sensorless manipulation by using a simple method to orient planar objects. This method involved sliding a randomly oriented object into walls, along walls, and into corners, sometimes with the effect of reducing the number of possible orientations. Goldberg [13] presented a similar concept of orienting polygonal object without using sensors. He used a parallel-jaw gripper to squeeze objects in various angles. Mason also discusses the problem of sensor dependency in [14]. These are the samples of the sensorless concept that led to the new concept of Bi-HR robot manipulator.

### 4. HYPER-REDUNDANT ROBOTIC MANIPULATORS AND PAST EFFORTS

The term "Hyper-Redundant" was first used in the robotic area by Chirikjian and Burdick in [15]. However, the earliest hyper-redundant robot designs/ implementations were presented in the 1960's [16]. The word 'redundant' indicates that the number of actuated degrees of freedom exceeds the minimal number required to perform a particular task. The following are examples of the past efforts in hyper-redundant manipulators.

#### 4.1 *The ACM III (Locomotion Device) by Hirose*

The ACM III was constructed and first tested in 1972 by a famous Japanese researcher, Prof. Hirose [17]. Hirose was inspired by the motion of real snakes. The ACM (active cord mechanism) was driven by a servomechanism, and consisted of 20 joints with a 2 meter length. (See Figure 2)

#### 4.2 *The 30 DOF Planar Hyper-Redundant Manipulator by Chirikjian and Burdick*

In order to demonstrate and validate the hyper-redundant kinematic works by Chirikjian and Burdick, a planar hyper-redundant manipulator was constructed [7-9]. This manipulator is a 30 DOF VGT structure consisting of 10 identical three DOF truss modules. (See Figure 3) Each module contains 3 prismatic joints. These prismatic actuators are driven with DC servomotors and lead screws.

#### 4.3 *Elephant Trunk Manipulator by Walker*

In 2001 Hannan and Walker reported a design and implementation of the 'Elephant Trunk' manipulator shown in Figure 4 [18]. The backbone of the manipulator was composed of a serial connection of 16 two-DOF joints with the overall length of 32 inches. The manipulator was divided into four independently actuated sections which vary in diameters. A cable servo system was used to actuate these sections.

#### 4.4 *The Modular Reconfigurable Robot by Mark Yim*

Modular reconfigurable robotics is an approach to building robots for various complex tasks. Instead of designing a new and different mechanical robot or components for each task, many copies of one simple module are built. Many applications have been determined, such as, locomotion, manipulation, etc. One can categorize this type of robot as a hyper-redundant robot as well. Figure 5 shows a configuration of a modular reconfigurable robot (see e.g., [19]).

#### 4.5 *Serpentine Robot by Howie Choset*

Howie Choset has explored and developed a number of motion planning algorithms for highly articulated serpentine robots. Articulated serpentine robots are a type of hyper-redundant manipulators, that were developed at Carnegie Mellon University. Figure 6 is

an example of a serpentine robot, demonstrating its rescue operation (see e.g., [20]).

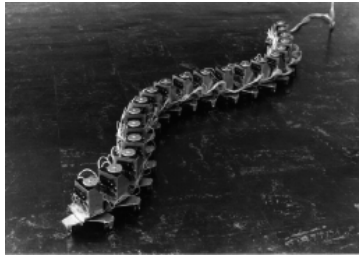


Figure 2: ACM III by Hirose [17]

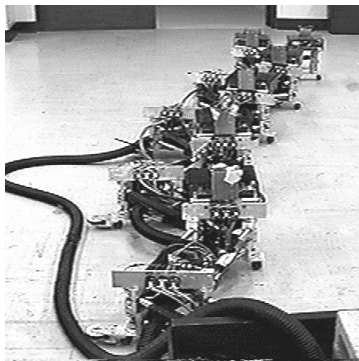


Figure 3: The 30 DOF Hyper-Redundant Robot by Chirikjian and Burdick [7-9]



Figure 4: Elephant Trunk by Hannan and Walker [18]

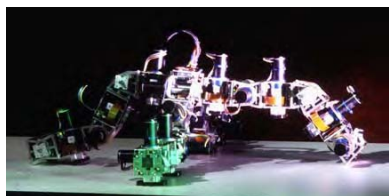


Figure 5: Modular Robots by Mark Yim [19]



Figure 6: Serpentine Robot by Choset [21]

## 5. PAST EFFORTS ON BINARY HYPER-REDUNDANT ROBOT MANIPULATORS

The sensorless concept leads to the design concept of the binary manipulator to reduce the complexity of control systems and computer interfacing. A planar serial revolute ‘digital manipulator’ is discussed in Pieper's famous thesis from 1969 [21]. Roth *et al.* [22] summarizes several studies of using computer control of mechanical manipulators.

In 1994, Chirikjian and his co-workers, influenced by the concepts mentioned above, implemented several binary manipulators, developed in the robot and protein kinematics lab at Johns Hopkins University.

### 5.1 Planar Binary Robot Manipulator at Hopkins

This manipulator consists of five 3-bit planar VGT modules. Pneumatic cylinders are used as actuators because of their low cost, lightweight, and sufficient force. This manipulator is designed to manipulate objects in two dimensions only. One end of the manipulator is attached to a base, while the end-effector has a two-state gripper. The total number of actuators (bits) is  $3 \times 5 (=15)$ , which provides  $2^{15} (=32,768)$  reachable positions in 2-dimensional space. The manipulator is controlled by the user who inputs a binary number (0 or 1) for each individual actuator.

### 5.2 Ebert-Uphoff Binary Robot Manipulator at Hopkins

This is the 3-dimensional binary robot manipulator influenced by the Stewart platform. The manipulator consists of 6 modules, and one end is vertically attached to the structure from the top (ceiling-liked). A 3-D gripper (X, Y, and theta) is attached at the end of end-effector. Each module consists of 6 binary actuators. Thus, the end-effector can reach a total of  $2^{6 \times 6}$  (~68.7 billion) different positions in 3-D space.

### 5.3 Suthakorn Discretely-Actuated Hyper-Redundant (DAHR) Robotic Manipulator at Hopkins

This robotic manipulator was designed and built by the author while working towards the PhD degree at the John Hopkins University. The design uses 3-bit binary VGT modules stacked on top of each other with a discretely actuated rotating joint between each module. As a result the manipulator has the ability to reach many points and covers a full 3-dimensional sphere around the manipulator itself. The prototype consists of three modules of 3-bit binary VGTs, and each rotating joint between each module has 16 steps. This configuration makes the prototype have  $2^{3 \times 3} \times 16^3$  (~2.1 million) discrete states. A full detail of the design and construction will be reported in [24]. (See Figure 7)

## 6. PRO AND CONS OF THE BI-HR ROBOTS AND EXAMPLE OF ITS APPLICATION

In this section a list of advantages and disadvantages of the Bi-HR manipulator, and examples of Bi-HR

manipulator applications are presented with examples of its applications.

### 6.1 Advantages

- Discrete states and high repeatability
- Relatively low cost and light weight
- High capacity load to manipulator weight ratio
- No need for feedback control
- Less complexity in computer controlled interfacing
- Allow tasks to be performed even when some actuators fail
- High ability in obstacle avoidance

### 6.2 Disadvantages

- Has non-continuous (discrete) workspace
- Requires more cascaded modules to improve its performance (number of reached states)
- Requires a large amount of computations in inverse Kinematics

### 6.3 Examples of Bi-HR Manipulator Applications

- Inspection and repair tasks in highly complex or difficult to access environments such as space stations, bridges, chemical plants, ducts and pipe.
- Search and rescue tasks in difficult to access areas.
- Medical applications, such as, endoscope systems.
- Locomotion in rough terrain

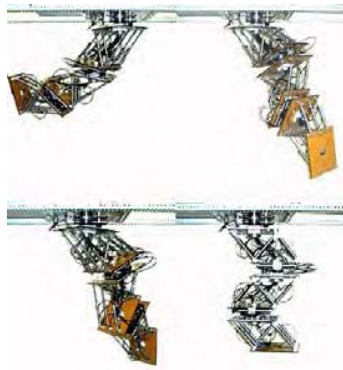


Figure 7: Some Configurations of Suthakorn's DAHR

## 7. SUMMARY

This paper discussed several basic concepts of the Bi-HR manipulator, e.g., adaptive structures, sensorless systems, and binary manipulators. Descriptions with examples of hyper-redundant manipulators are introduced. Previous efforts on the concept are described. Finally, a list of advantages and disadvantages of this manipulator type is presented with examples of its applications.

## 8. REFERENCES

- [1] Wada, BK, "Adaptive Structures: An Overview," *J. Spacecraft*, 27(3), June 1990, pp. 330-337.

- [2] Miura, K, and Furuya, H, "Variable Geometry Truss and Its Application to Deployable Truss and Space Crane Arm" *Acta Astronautica*, 12(7, 8), 1995.
- [3] Rhodes, MD, and Mikulas, MM, "Deployable Controllable Geometry Trusses Beam," *NASA TM 86366*, 1985.
- [4] Hughes, PC, Sincarsin, WG, and Carroll, KA, "Trussarm-A Variable Geometry Truss Manipulator," *J. of Intell. Mater. Syst., and Struct.*, Vol. 2, April 1991, pp. 148-160.
- [5] Robertshaw, H, and Reinholtz, C, "Variable Geometry Trusses," *Smart materials, Structures, and Mathematical Issues*, 1998, pp. 105-120.
- [6] Nacarato, F, and Hughes, PC, "Inverse Kinematics of Variable Geometry Truss Manipulators," *J. of Robot Systems*, 8(2), 1991.
- [7] Chirikjian, GS, "Kinematics Synthesis of Mechanisms and Robotic Manipulators with Binary Actuators," *ASME J. Mech. Design*, 121, 1995.
- [8] Chirikjian, GS, "Theory and Applications of Hyper-Redundant Robotics Manipulators," *PhD Dissertation, Cal Tech.*, 1992.
- [9] Chirikjian, GS, and Burdick, JW, "Kinematically Optimal Hyper-Redundant Manipulator Configurations," *IEEE Trans. on Robotics and Automation*, 11(6), Dec 1995, pp. 123-136.
- [10] Chirikjian, GS, "A Binary Paradigm for Robotic Manipulators," *Proc. of the IEEE ICRA '94*, May 1994.
- [11] Suthakorn, J, and Chirikjian, GS, "A New Inverse Kinematics Algorithm for Binary Manipulators with Manu Actuators," *Advanced Robotics*, 15(2), 2001.
- [12] Erdmann, MA, and Mason MT, "An Exploration of Sensorless Manipulation," *IEEE J. of Robotics and Automation*, 4(4), 1988, pp. 369-379.
- [13] Goldberg, KY, "Orienting Polygonal Parts without Sensors," *Algorithmica*, 1993, pp. 201-255.
- [14] Mason, MT, "Kicking the Sensing Habit," *AI Magazine*, Spring 1993, pp. 58-59.
- [15] Chirikjian, GS, and Burdick, JW, "An Obstacle Avoidance Algorithm for Hyper-Redundant Manipulators," *Proc. of IEEE ICRA '90*, Cincinnati, OH, May, 1990.
- [16] Anderson, VV, and Horn, RC, "Tensor-Arm Manipulator Design," *ASME Trans, Vol. 67-DE-57*, 1967, pp. 1-27.
- [17] Hirose, S, "Biologically Inspired Robots, Snake-Like Locomotors and Manipulators," *Oxford University Press*, 1993.
- [18] Hannan, MW, and Walker, ID, "The 'Elephant Trunk' Manipulator, Design and Implementation," *Proc. of the 2001 IEEE/ASME AIM*, Italy, 2001.
- [19] Yim, M, "A Reconfigurable Modular Robot with Manu Modes of Locomotion," *Proc. of 1993 JSME Int'l Conf. on Adv. Mechaton*, Japan, 1993.
- [20] Hickman, F, Henning, W, and Choset, H, "Motion Planning for Serpentine Robots," *ASCE Space and Robotics*, USA, 1998.
- [21] Pieper, DL, "The Kinematics of Manipulators under Computer Control," *PhD Dissertation, Stanford University*, 1969.
- [22] Roth, B, Rastegar, J, and Scienman, V, "On the Design of Computer Controlled Manipulators," *Proc. of the 1st CISM-IFTMM Symp. On Industrial Electronics*, 1999.
- [23] Ebert-Uphoff, I, "On the Development of DAHSPM," *PhD Dissertation, Johns Hopkins University*, 1996.
- [24] Suthakorn, J, "Paradigm for Service Robotics," *PhD Dissertation, Johns Hopkins University*, 2003.