Design and Construction of A New 3-D Binary Hyper-Redundant Robotic Manipulator, 'The MU-BHR Manipulator'

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Abstract. Continuous actuators, such as motors, operate most robotic manipulators. These actuators require complex and expensive control and sensor systems. In this study, binary hyper-redundant (BHR) robotic manipulators are shown to be viable candidates for use in applications where high repeatability and reasonable accuracy are required. Such applications include pick-and-place, spot welding and assistance to people with disabilities. This paper discusses the design, construction, and properties of a new 3-D binary hyper-redundant (BHR) robotic manipulator prototype, "The MU-BHR Manipulator." The new prototype consists of 5 various sizes of 3-bit binary-actuated variable geometry truss (VGT) modules stacked on top of each other with a specially designed 4-step connecter between each module. This configuration makes the prototype have $2^{3x5}x4^5$ (~33.5 million) discrete states. The manipulator has the largest module at the base, and the module sizes are decreased from the base toward the end-effector to reduce problems occurring by manipulator inertia. The specially designed connector uses a force absorbing material while acting as a damper. This study results in a new generation of a low-cost and light-weight robotic manipulator with a benefit of the vibration reduction

Introduction

Continuous actuators, such as motors and hydraulic cylinders, actuate most robotic manipulators. These actuators require complex and expensive control and sensor systems. In this study, binary hyper-redundant (BHR) robotic manipulators are shown to be viable candidates for use in applications where high repeatability and reasonable accuracy are required. Such applications include pick-and-place, spot welding and assistance to people with disabilities.

The BHR 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 BHR 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. Generally, the DAHR manipulator is relatively inexpensive, lightweight, and has a high payload to arm weight ratio.

This paper describes the design, construction, and properties of a new 3-D binary hyper-redundant (BHR) robotic manipulator prototype, "The MU-BHR Manipulator." The new prototype consists of 5 various sizes of 3-bit binary-actuated variable geometry truss (VGT) modules stacked on top of each other with a specially designed 8-step connecter between each module. This configuration gives the prototype $2^{3x5}x8^5$ (~1073 million) discrete states. The manipulator has the largest module at the base, and the module sizes are decreased from the base toward the end-effector to reduce problems occurring by manipulator inertia. The specially designed connector uses a force absorbing material while acting as a damper. This study results in a new generation of a low-cost and light-weight robotic manipulator which has reduced vibration.

Influencing Research and Background

In this section, the three concepts which influenced important features of the Binary Hyper – Redundant manipulator in this study are discussed.

Concept of Adaptive Structure. 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, including several different types of adaptive structures. 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 lead Miura and Furuya [2] in Japan and Rhodes and Mikulas [3] in the U.S.A. to explore new possibilities of adaptive structures. The kinematics, dynamics, and vibrations of VGT manipulator have become important research topics. Robertshaw and Reinholtz [4] 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, Nacarato and Hughes [5] discussed an early version of inverse kinematic analysis of VGT manipulators. Then, Chirikjian and his co-workers (e.g., [6-10]) presented a number of kinematic analyses, and trajectory planning which they were able to apply to the VGT manipulator.

Concept of Sensorless System. The second concept was the sensorless system. This concept was discussed by a number of researchers. Erdmann and Mason [11] 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 [12] presented a similar concept of orienting a 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 [13]. These are samples of the sensorless concept that led to the new concept of Bi-HR robot manipulator.

Concept of Hyper – Redundant Manipulators. The term "Hyper-Redundant" was first used in the robotics area by Chirikjian and Burdick in [14]. However, the earliest hyper-redundant robot designs/implementations were presented in the 1960's [15]. The word 'redundant' indicates that the number of actuated degrees of freedom exceeds the minimal number required to perform a particular task. Examples of past efforts in hyper-redundant manipulators are such as, [16 – 19].

Previous Work in Binary Manipulators

This section discusses three previous works in binary manipulators which may influence our new design of the MU – BHR manipulator.

The Planar Binary Robot Manipulator. This manipulator consists of five 3-bit planar VGT modules [20]. Pneumatic cylinders are used as actuators because of their low cost, light weight, 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 endeffector has a two-state gripper. The total number of actuators (bits) is 3x5 (=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. Fig 1. illustrates the manipulator.

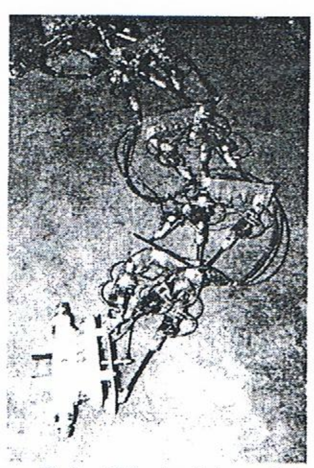


Fig. 1: The Planar Binary Robot Manipulator – Johns Hopkins University [20]

The Ebert – Uphoff Binary Robot Manipulator. This is the 3-dimensional binary robot manipulator influenced by the Stewart platform [21]. The manipulator consists of 6 modules, and one end is vertically attached to the structure from the top (ceiling-like). A 3-D gripper (X, Y, and theta) is attached at the end of the end-effector. Each module consists of 6 binary actuators. Thus, the end-effector can reach a total of 2^{6x6} (~68.7 billion) different positions in 3-D space. Fig. 2. shows the Ebert–Uphoff Manipulator.

Discretely-Actuated Hyper-Redundant (DAHR) Robotic Manipulator. This robotic manipulator was designed and built by the first author while working towards the PhD degree at 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 $2^{3x3}x16^3$ (~2.1 million) discrete states. Full detail of the design and construction will be reported in [22]. (See Fig. 3)

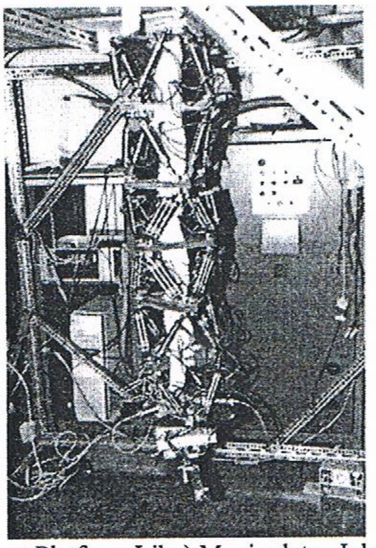


Fig. 2: Ebert-Uphoff (Stewart Platform-Like) Manipulator-Johns Hopkins University [21]

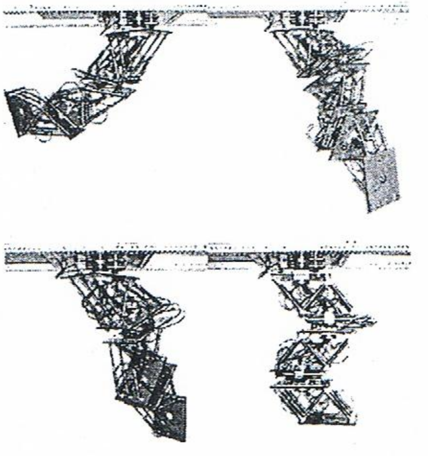


Fig. 3: Example Configurations of the Suthakorn's Discrete Actuated HyperRedundant Robotic Manipulator -Johns Hopkins University [22]

Design and Construction of "The Mahidol University-Binary Hyper-Redundant Manipulator"

Appearance and General Properties of the MU-BHR. 'The MU-BHR' consists of five modules of 3-Bit Binary-VGT, which are stacked on top of each other to form a chain or snake-like manipulator. The size of each module varies from the largest to the smallest, with the biggest module located at the base. The module's varied size concept is applied to increase the payload. Fig. 4. shows the 8 possible configurations of a 3-Bit Binary VGT module.

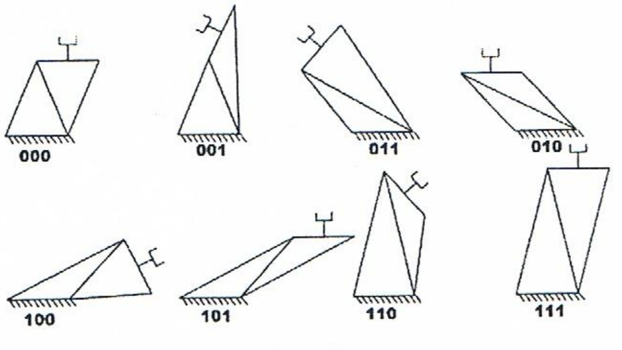


Fig. 4: 8-Possible Configuration of a 3-Bit Binary VGT Module

Four vibrating absorbers are used as a set of connecting joints between modules as a set of spring-dashpots, which help the manipulator to be more flexible, and also to absorb vibrations, occurring in the mechanism (See Fig. 5). These four points are also the joint's connectors, which allow the manipulator to be adjusted in the direction of each module to suit any task with an increment of 90 degrees. Each module has a total of 8 (=2^3) possible configurations. The number of reachable points of the manipulator is exponential to the number of actuators, multiplied with the number of joints exponential to the number of each joint's degrees of freedom. S o, the total number of MU-BHR manipulator's reachable points is approximately 33.5 million points ($2^{15} \times 4^5 \cong 33.5 \times 10^6$). The manipulator's retract/extend length ratio is 1:1.5, where the extended length is 1.30 meters.

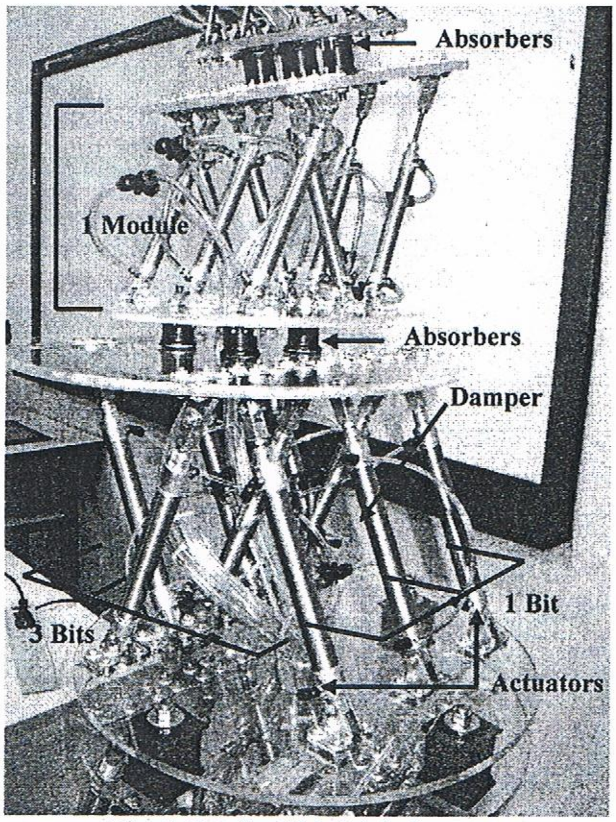


Fig. 5: Details of Module's Structure

Design of A Module. Each module is a 3-Bit Binary VGT, which consists of 3 bits and 2 plates to fix all actuators. These plates are upper and lower plates. Acrylic is used as the plate material because of their light weight and ease of machining. Pneumatic cylinders are selected here. Each bit consists of three cylinders connected in parallel, where two of three cylinders are actuators, and the last one (located in the middle position) is a dashpot. The dashpot is a cylinder modified by filling oil into the cylinder, and connecting it to be a closed system. This concept is used to decrease the acceleration of the pneumatic system for the purpose of vibration-reduction. See Fig. 5 for the module's details.

Design of the Manipulator. The MU – BHR manipulator consists of five modules, stacked on top of each other from the largest to the smallest (See Fig. 6.) The management of pneumatic air tubes is also an important issue that has been taken care of. All air tubes are organized and inserted through the center line along the manipulator to avoid any problem during operations. The manipulator is fixed to a 1m x 0.6m wood sheet, which is easily installed in different styles: upward or downward vertical style, or wall type.

Control System of the MU-BHR Manipulator

The control system of the manipulator can be separated into two parts: an electronic control system, and a pneumatic control system. The brief control architecture is described here (See Fig. 7.) The manipulator can be controlled or pre-programmed by using a PC to interface with a micro-controller/relay circuit. The circuit is a home-made micro-controller/relay circuit which produces a set of solid-state commands and sends them to the pneumatic control system. The circuit is shown in Fig. 8. The pneumatic control system consists of 16 solenoid valves to control air direction in each bit (15 valves for 15 bits and 1 valve for the gripper). Fig. 9 shows the manipulator and its control system.

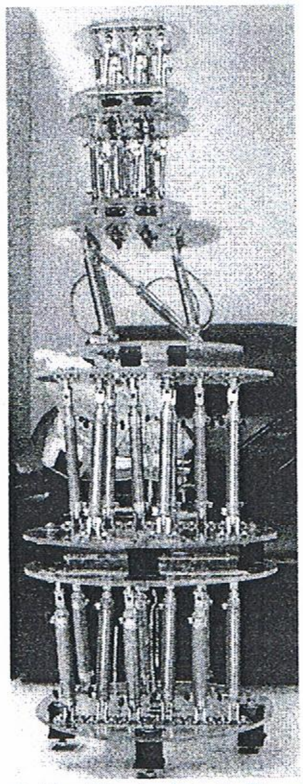


Fig 6: The Manipulator's Structure

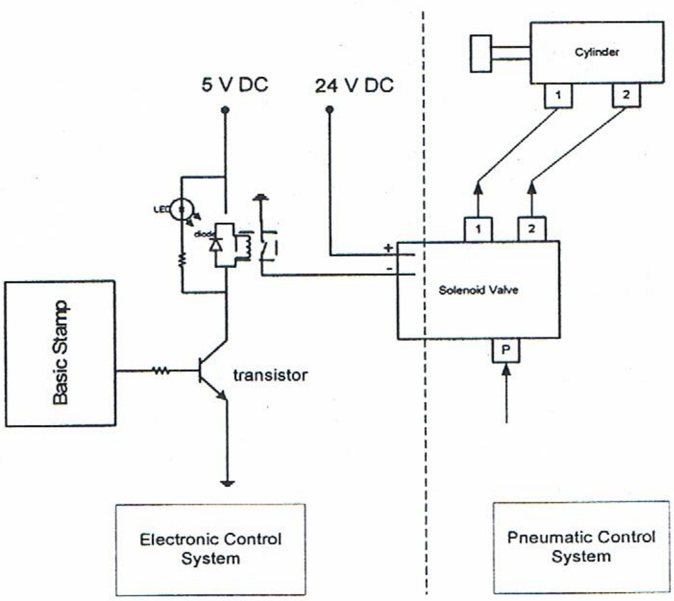


Fig. 7: Control Architecture of One-Bit System

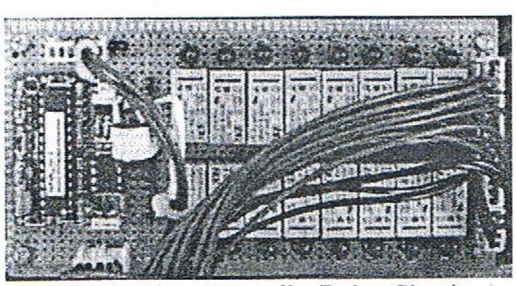


Fig. 8: Micro-Controller/Relay Circuit

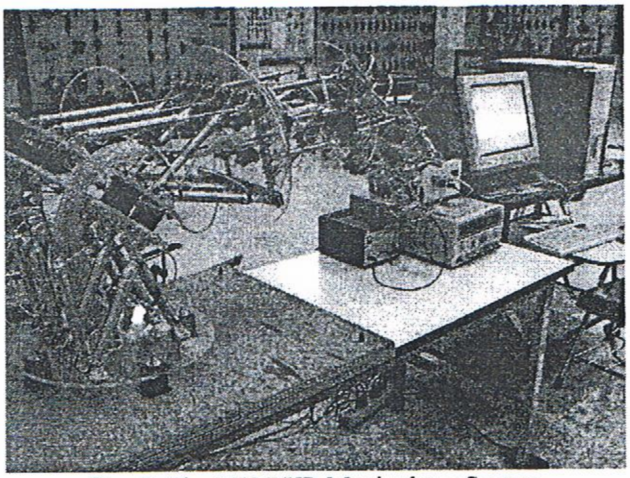


Fig. 9: The MU-BHR Manipulator System

Demonstrations of the MU – BHR Manipulator

The demonstrations consist of two sections, 1) 8-configuration of one module, and 2) path-following demonstration.

8-Configuration of One Module. This demonstration shows the operation of only one module. Fig. 9 shows the 8-configuration performed by a 3-bit binary VGT module.

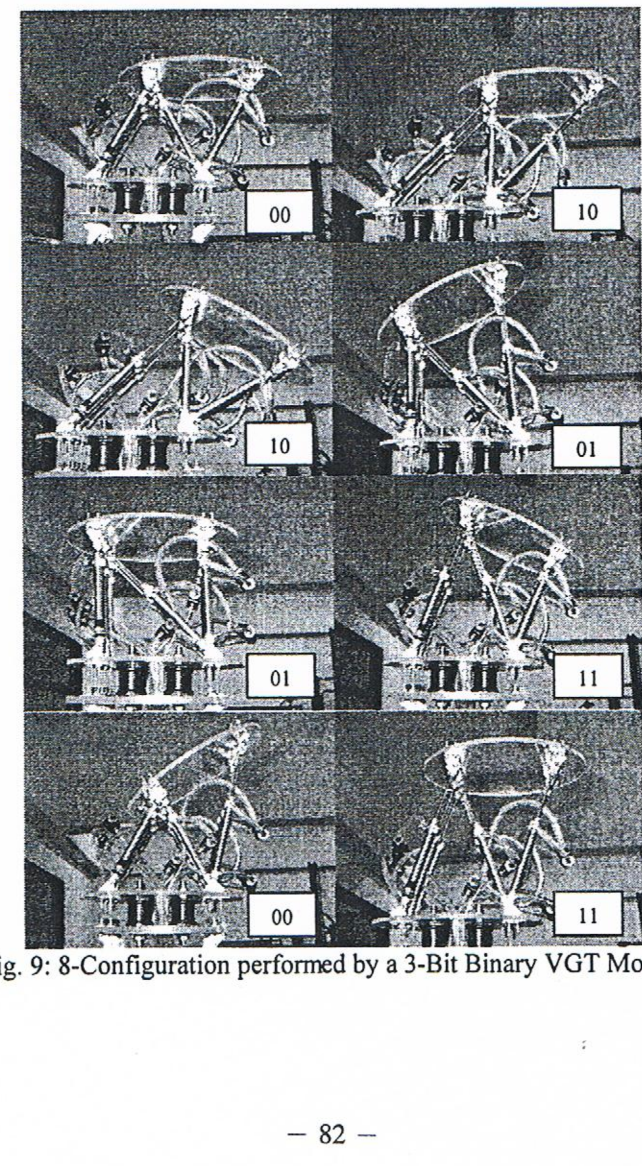
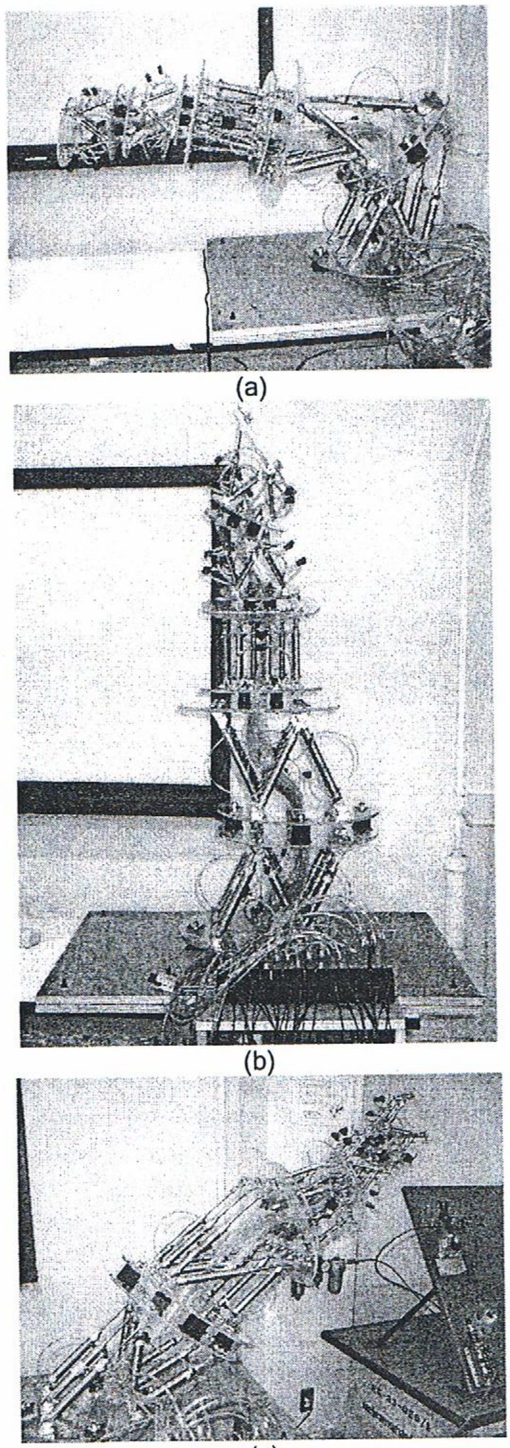


Fig. 9: 8-Configuration performed by a 3-Bit Binary VGT Module

Path Following Demonstration. This demonstration shows the manipulator motions, when the end-effector is controlled to move from a starting point to an end point. Video clips are captured for analyzing purposes. Fig. 10 shows a series of manipulator motions.



(a)

(b)

(c)

Fig. 10: Example images from path following demonstration

Conclusion

This paper described motivations, background, design and demonstrations of a new kind of manipulator, the binary hyper-redundant manipulator. The prototype manipulator, called MU-BHR manipulator, consisted of 5 varied sizes of 3-bit binary VGT module. The manipulator was actuated by a set of pneumatic cylinders, connected in a format of series/parallel structures. The demonstrations showed the high potential of the BHR manipulator in pick-and-place applications, in which high repeatability and reasonable accuracy were required. Several parts were selected and modified from off-the-shelf materials; therefore, many problems still occurred. Although dashpots/dampers were used for vibration-reduction purposes, vibrations were still noticeable.

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