

Design and Control Architecture of a 3D Printed Modular Snake Robot

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Abstract—In this paper the design and construction of a 3D printed snake robot is presented. This snake robot has been designed to be able to complete a wide variety of tasks and motions that other snake robots are currently able to perform, such as serpentine motion, rolling and the ability to climb some objects. An approach is also investigated which allows the snake robot to be attached to the end of a serial manipulator robot to increase its available degrees of freedom. A modular design has been focused on, allowing for the fast and low cost generation and implementation of the robotic snake.

Index Terms—snake robot, modular robotics, robot, Dynamixel servos, 3D printing

I. INTRODUCTION

There are many different types of robots existing in the world today. When robots that operate on the land are considered, generally tracked or wheeled robots are used. There are many challenges that have arisen that these types of robots are unsuitable for, such as the navigation of unstable terrain such as in a collapsed building or when navigating in tight spaces like the inside of a pipe. To overcome these challenges snake robots, a many degree of freedom modular robot, have been developed. These type of robots use their many internal Degrees of Freedom (DOF) to thread through tightly pack spaces, allowing the robot to have access to locations where people or machinery cannot [1]. These robots can coordinate their internal DOF to perform a variety of movements like crawling, climbing and swimming, making it suitable for number of applications such as search and rescue in disaster site, inspection of narrow and unstructured environments like collapsed buildings and even in reconnaissance situations [2], [3]. A snake robot can also be used as end effector of a manipulator to increase the number of DOF of the robot.

This paper presents a modular snake robot that combines the strengths of the current state of the art designs discussed in background section. This snake robot has been developed to achieve complicated tasks such as: climbing, smooth serpentine motion, and increase a ABB Industrial Manipulator robot's DOF. The following paper is organized as follows: Section II presents the current research that is being conducted using snake robots. Section III details a design for a snake robot that is able to achieve the proposed tasks. Section IV presents

the control architecture of the snake robot. Details on how the designed system has been tested is provided in section V. Finally, the paper is concluded and future work is presented in Section VI.

II. BACKGROUND

Before the construction of the snake robot began, research was conducted into the various different forms of snake robots that have currently been implemented refer [4]–[7]. A description of the main variants of the snake robot are as follows.

The first model of snake robot investigated was the CMU modular snake robot. This type of snake robot is able to move in a 3D manner, which allows it complete a wide variety of movements, such as climbing and linear progression, sidewinding, rolling, cornering and pipe rolling [8], where its primary form of motion is the corkscrew motion. This robot was designed with expandability in mind, as each of the segments that make up the snake robot being exactly the same, with the exception of the head and tail of the robot. Each of these unique segments contain only a single DOF, but when combined give the robot n degrees of freedom, relative to the length of the snake [8]. This snake robot was initially prototypes using a 3D printer, and is now constructed with aluminum and a rubber to provide grip and durability. This snake robot is powered and controlled via a tether [4], which makes it unable to navigate too far away from a base station. This tether could also potentially become entangled on various objects in the environment.

The next robot that was considered was the ACM-R5. This robot is the most advanced in the ACM snake robot family by Hirose and Yamada [3]. ACM-R5 is an amphibious snake robot which has ability to move both on the land and in the water. This snake robot is composed of 9 Modular Universal Units [5]. Each of these modules have two degrees of freedom with an on-board CPU and power unit. This robot has passive wheels attached which allows it to move quickly on a smooth surface. It is waterproofed using O-rings and other water proofing accessories so that it can move smoothly in the water. It can perform different motions like serpentine locomotion, concertina movement, sidewinding, S-shape and

E-shape rolling, Arc-shape rolling and helical rolling but its primary motion is serpentine movement [5]. The disadvantage of this robot is it cannot climb.

Unlike the previous two snake robots considered, the next snake robot is of a different kind developed by OC robotics, the snake-arm robot [9]. This is a fixed robot, mainly being used in manufacturing applications as well as being able to be used in hazardous environments, such as a nuclear power plant. This robot has a fixed base which accommodates all the actuation and electronics required to move the robot. It is driven by a wire rope and controlled via software to get to the desired positions. It is designed with a hollow core, so cabling, hoses and other equipment can be routed through the center of arm. There are two types of snake-arm robots available for these applications, the spatial snake-arm robot and planar snake arm robot. The first robot, the spatial snake arm robot, has a total of 12 links with two DOF each. This provides a total of 24 DOF to the system. These robots are mounted on a linear axes from a fixed position, and is then deployed into the environment. This allows the robot to have sturdy base in-which to operate from, but still allows motion in a single axis in conjunction with the arm itself. This robot can also be utilized by mounting it to a mobile robot, or by attaching it to the end of a manipulator robot to increase the DOF of the robot. The second robot is planar snake robot. This robot only has the capacity to articulate itself in one plane. This robot is very compact, as it is able to save space by coiling around an actuator pack.

After analyzing the aforementioned snake robots, the strengths and weakness can be obtained. The CMU robot is very versatile as it has the ability to move with most types of snake movement, but it lacks the ability to traverse in the traditional serpentine type movement. Conversely, the ACM-R5 robot is able to use this type of movement, but is able to climb up different types of objects. The third type of robot, the snake arm robot, does not use a modular design but is able to achieve a high DOF by utilizing a series of cables attached to motors within its base. These strengths and weaknesses were considered during the design phase of the presented robot.

III. DESIGN

Each module of the 3D printed modular snake robot functions as single rotational joint with one Degree of Freedom (DOF). Every module is able to rotate 90 degrees with respect to previous module, thus enabling the generation of movement utilizing many different methods. Each module is connected to the previous module in such a way that the axis of rotation is perpendicular with respect to previous one. Having two different axis of movement in each segment pair, means that the robot is able to generate movement in all three axis given at least four segments in the chain. In other words, the modules allow for movement in both the vertical and horizontal axis, thus enabling the robot to move in a three dimensional plane. The current design consists of 16 modules including a head and tail module, which can be altered depending on the application. Having this many modules provides 16 DOF,

which can be increased or decreased by simply adding or subtracting the amount of conjoined modules. Each module is 2.15 inches (5.48 cm) in diameter, and has a length of 2.95 inches (7.5 cm) in-between the joint axes.

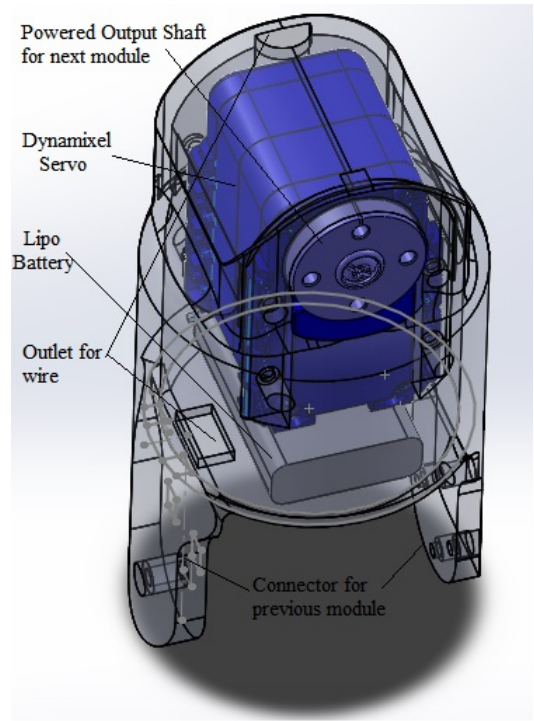


Fig. 1. Components of 3D Printed modular snake robot

As shown in the figure 1 the module consists of a housing, a Dynamixel servo motor, a Lithium polymer (LiPo) battery and an internal channel that allows the communication and power cables to be passed down the chain. The housing is constructed via 3D printing using PLA, a commonly used biodegradable 3D printing material, which contains all of the components within the module. The Dynamixel motor provides the torque and velocity required to provide movement to the next module. Every module has a single cell (1s) 3.7V LiPo battery inside of it, which is connected with two other modules in series to make up the 11.1 volts required to power the segments. Because of this, pairs of three modules should always be used. Each segment's power is then connected in parallel to the rest of the snake. This will allow for any of the modules to always have enough current available to them to provide the maximum torque possible to each of the motors. It will also ensure that each segment of the snake will always be powered while the other segments of the snake are able to operate.

A. Housing

The housing consists of two parts, these being the front housing and rear housing. The front housing is the main part of the module. This contains space to house both the battery and the servo motor. To accommodate for the wires providing both communication and power to the next module, parts of

the wall of the module were thinned slightly. This was done in a circular pattern around the module, as opposed to only been done in a single place, to reduce a weak-spot being made in the housing wall. The rear housing acts as a cap to cover the module. Figure 2, depicts the front and rear housing of the robot.

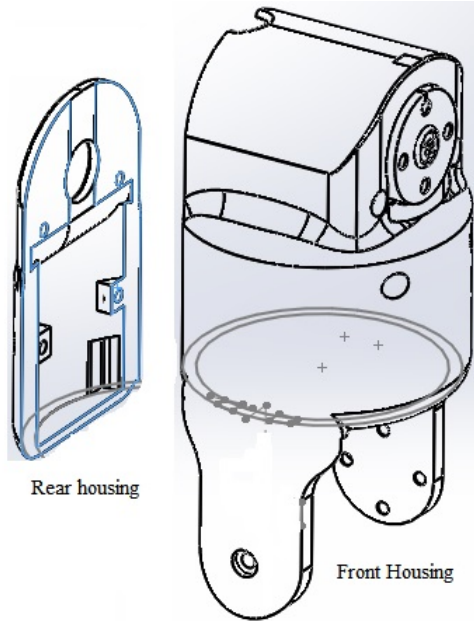


Fig. 2. Snake Robot Housing

To enable the many different types of movement present when snake robots are considered, a cylindrical design for the housing has been chosen. Having a cylindrical design is optimal for both rolling and climbing activities. This housing is designed in such a way that any part of the robot will not exceed 2.16 inches (5.5cm) in diameter. As the center part of the body is cylindrical, it can accommodate the structure for the passive wheel adapter, which can be attached and detached depending on the application. This passive wheel adapter will allow the robot to be able to easily preform the types of movement that a cylindrical body is not ideal for, such as the serpentine type movement.

B. Passive Wheel Adapter

As shown in figure 3, the passive wheel adapter consists of six passive wheels to be placed 60 degree apart and attached to the passive wheel support. The wheel adapter also has a small opening in the support so that it can slide over each of the modules. A screw and bolt can then be used to fasten the passive wheel support together, which enables the structure to be attached to the module. Thus with the help of this device, fast serpentine motion can be achieved whilst not sacrificing the ability for the snake robot to preform the other types of motion when required.

C. Actuation

Many different types of Actuation can be used for snake robots such as pneumatic, electric motor, servos, cable ac-

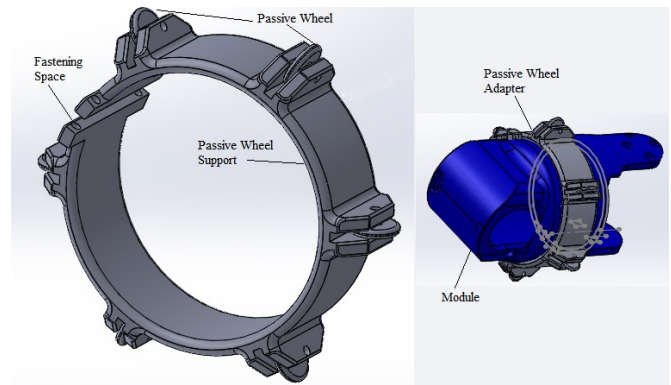


Fig. 3. Passive Wheel Adapter

tuation or driven wheels [9], [10]. For this robot, servo motors were considered. The Dynamixel servo motor was the chosen servo motor type, as these servo motors have an on board microprocessor to provide bus communication, positional feedback, temperature and load monitoring [11]. These motors also have adjustable torque speed and response control with Position, load, voltage, speed and temperature feedback enabling the formation of a closed loop control system with relative ease. The servos use TTL or RS-485 serial communication and allows for a daisy-chain bus connection at up to 1-3Mbps. The control algorithm used to maintain the shaft positions on the servo can be adjusted individually for each servo, allowing the user to control the speed and strength of the motor's response. All of the sensor management and position control is handled by the servo's built-in microcontroller. Out of the range of Dynamixel servos available, the AX-12A servo was chosen for this application [11]. This version of the servos is the most affordable servo with built in microcontroller. It operates at 12V 900mA, weighs 55g and provides a stall torque of 15.3 kg.cm. These servos use TTL half-duplex asynchronous serial communication as well as including all of the features mentioned above. Thus due to these advantages and the affordable cost of the servo, this servo motor was chosen and implemented in this application.

D. 3-D Printing

The technique of 3D printing is used to prototype the casing of this robot. 3D printing, or additive manufacturing, is a process of creating three dimensional solid objects from a digital file [12]. The creation of a 3D printed object is achieved using the additive processes, as opposed to the subtractive process used by most other techniques, such as by a CNC machine. The process utilized by this additive manufacturing machine involves an object being created by laying down successive layers of material on top of each other until the whole object is created, referred to as the Fused Deposit Modeling method. Each of these layers can be seen as a thinly sliced horizontal cross-section of the eventual object [13]. The digital file of the object to be printed is made using a 3D scanner, to copy an existing object, or in a Computer Aided Design (CAD) program for the creation of a totally new

object. After the model has been completed, the file can then be saved in a general file type, such as the STL format, which is processed by software known as a slicer. This software converts the model into a series of thin layers and produces a G-code file containing instructions tailored to a specific type of 3D printer which enables the printer to create the model.

3D printing helps in the fast prototyping process which saves time and money. This is a big advantage as if the same parts were to be manufactured by hand it would take a significant amount of time to complete, as well as being very expensive due to the labor and machine costs involved. While 3D printing the first module, it was easy to find problems in the design, rectify it and then print the design again. Because of this, the design of the module was able to be easily changed to accommodate for new communication and power lines.

Each module of the snake robot was printed on the Lulzbot Taz 4 which is an open source 3D printer. It supports material such as PLA, ABS, HIPS, Ninja Flex etc. Among these materials, PLA (Poly-lactic Acid) was selected as it demonstrates significantly less part warping, higher maximum printing speeds, lower layer heights, sharper printed corners and affordable pricing compared to some of the other options. The virtual design for printing the module is designed in CAD software, in this case using SolidWorks, and saved in the STL format. This file is then opened in Cura LulzBot, which acts as the slicer and therefore converts the model into GCODE as well as allowing the user to control the operation of the 3D printer.

Unfortunately there are some disadvantages when using 3D printed parts of this nature, as they are generally not as strong, or as durable, as parts that might be constructed using other methods. Because of this, 3D printing is used for the prototyping stage of this robot. If this robot was to be taken to a potentially hazardous environment, such as a collapsed building or a site where there might potentially be corrosive material, the casing for the modules would need to be produced using either more traditional methods with stronger metal materials, or be constructed using an industrial grade 3D printer.

E. Implementation

The implementation is done both in software and hardware. Figure 4 shows the assembly of the module in the CAD software depicting all of the modules connected together to form the robot. This simulation helps to find the problems associated with the design and to study the movements of the robot before the physical models are produced. Figure 5 illustrates the model of the snake robot after the 3D printing process. As can be seen, all of the modules have been assembled to each other and wired showing the completion of the robotic snake.

F. Cost

A breakdown of the components and their cost are provided in Table I. The most expensive components of the robot are the Dynamixel servos. The features the servos provide are deemed worthy of the cost. Each servo has an on-board microprocessor

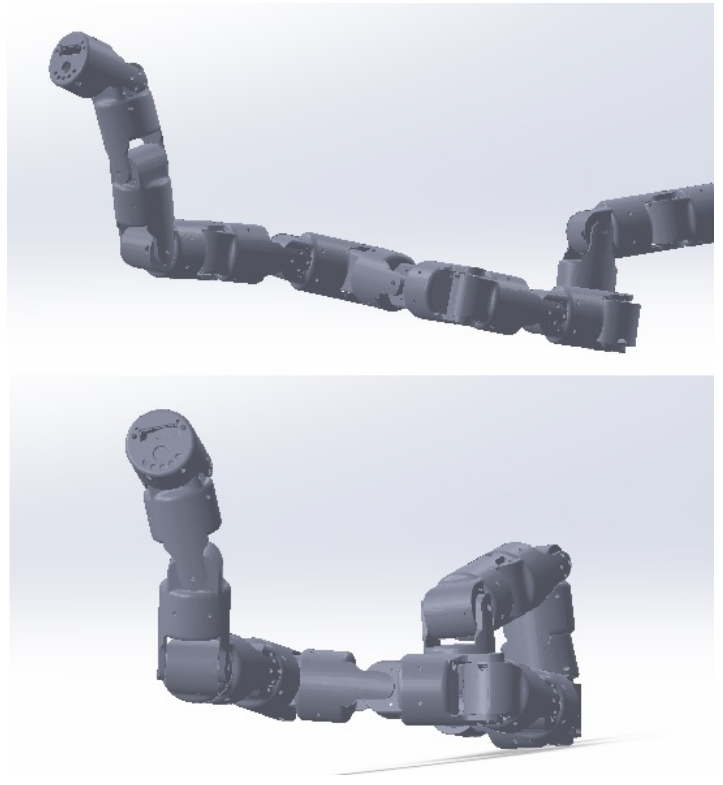


Fig. 4. CAD Model

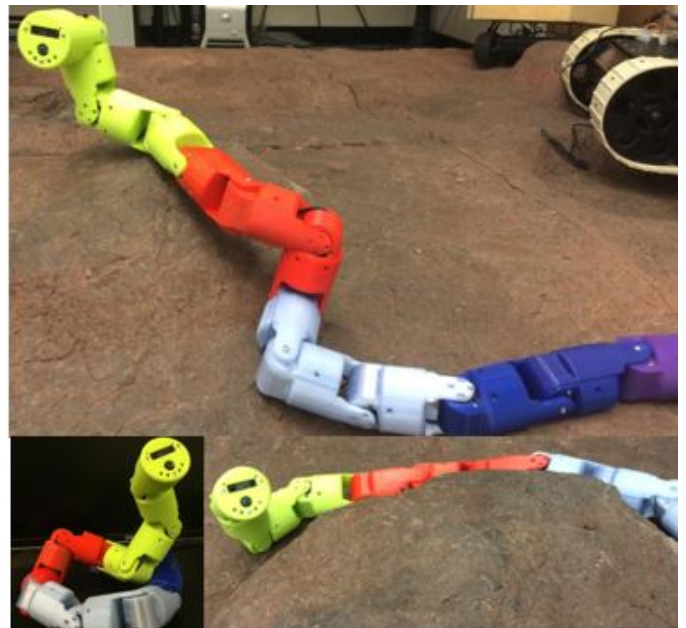


Fig. 5. 3D Printed Robotic Snake

that provides bus communication, motor state feedback such as positional, load, voltage, speed and temperature feedback [11]. Other relevant features enable the formation of a closed loop control system with relative ease as discussed under actuation section.

No	ITEMS	QTY	Unit(\$)	Total Cost(\$)
1	AX-12 Dynamixel Servo	16	\$37.50	\$600.00
2	USB2Dynamixel	1	\$49.90	\$49.90
3	Lipo Battery (3.7V 750mAh)	15	\$3.50	\$52.50
4	3D printing filament	1	\$24.95	\$24.95
5	Raspberry Pi Zero	1	\$5.00	\$5.00
6	USB Hub	1	\$10.99	\$10.99
7	Camera	1	\$33.90	\$33.90
8	IMU	1	\$29.95	\$29.95
9	IR Sensor	1	\$13.95	\$13.95
10	Wifi Module	1	\$8.99	\$8.99
11	Miscellaneous			\$65.00
			Total	\$895.13

TABLE I
MEASUREMENT RESULT OF EXP. I

IV. CONTROL ARCHITECTURE

Different approaches have been considered to control the presented robotic snake. The first approach that was considered is embedding a microcomputer directly into the head unit of the snake, such as an ODR0ID, Raspberry Pi or Raspberry Pi zero. This will allow for the local control of the robot, as Robotic Operating System (ROS) is able to run on-board. The next feasible approach that has been considered is to utilize a simple micro controller, such as the Arduino Nano or Arduino Mega 2560, equipped with a Wi-Fi module to enable communication back and fourth from a processing unit, such as a laptop. This will enable the use of ROS to control the robot for actuation, will also enable future applications. A description of the proposed setup is depicted in figure 6. The Raspberry Pi zero was chosen as the control unit for the system. The main reasoning behind this is that it is a very small and inexpensive microcomputer. It also has the advantage of having a form factor similar to that of a microcontroller, thus allowing the modular system to stay relatively small.

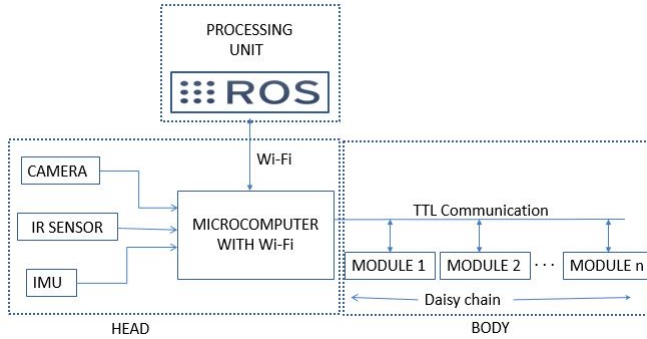


Fig. 6. Block Diagram

A. Processing Unit

There are many options for the processing unit that can be used, such as an ODR0ID, Raspberry Pi or Raspberry Pi Zero. Currently Robot Operating System (ROS) is installed onto a Raspberry Pi Zero which is able to control the angle of each of the connected servos, as well as interpret feedback from the servos such as position and temperature of each of each servos.

ROS is an open source meta-operating system that provides a message passing interface between processes across a network of installed nodes [14]. These nodes do not have to be located on the robot, which makes it ideal for a mobile robot as processing can be moved to another unit, assuming it is on the same network. Utilizing a common messaging systems such as ROS also allows the system to be easily integrated into a much larger system that is also utilizing this messaging system. This principle is being used at the moment as a Laptop is able to use the ROS environment to access and transmit information to and from the Raspberry Pi Zero.

B. Head

The head consists of a camera, an IR sensor, an IMU and the Raspberry Pi zero. The head is also equipped with an LED for illumination during pipeline inspection, at night and in a dark environment. The IR sensor is used to find the distance of an obstacle or an object in front the robot. This is helpful as it allows the robot to pick an object when the an end effector is attached to the head of the snake. An Internal Measurement Unit (IMU) with 10DOF is used, which gives 11 axes of data: 3 axes of accelerometer data, 3 axes gyroscopic, 3 axes magnetic (compass) and temperature which makes it possible for many different applications [15]. The microcomputer used is raspberry pi zero, which acts as a data exchange hub. All of the different sensors, as well as the servo motors, are attached to the Raspberry Pi Zero via a USB hub. Using a standard connection such as a USB, also enables for the rapid expandability of the system as many different sensors have this interface available. The Raspberry Pi zero collects all of the available data from the robot such as the camera, IR, IMU, Position, load, voltage, speed and temperature data and sends it to the processing unit via a Wi-Fi connection. The processing unit calculates the required positions that the servo needs to be in. This information is then transmitted to the microcomputer, which is able to move the attached servos to the desired positions.

C. Body

The body consist of a chain of modules connected together in series. The servos inside the module uses TTL serial communication to receive commands and send back sensor data to the microcontroller. A daisy-chain wiring scheme is applied to this system, in which multiple servo are connected together in a series sequence, thus reducing the number of wires required in the robot. This daisy-chain approach also allows for the system to be quickly scaled up or down as needed.

V. TESTING AND APPLICATIONS

The system has been tested to generate different types of 3D patterns by connecting the system directly to computer via a TTL to USB converter. A Dynamixel servo library generated for ROS was used, with the help of a python script to implement square wave motion as shown in Figure 7.

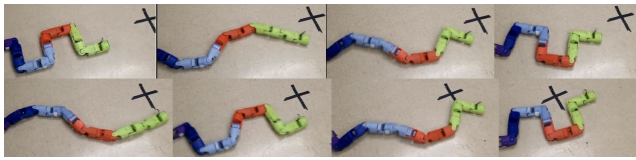


Fig. 7. Snake robot performing square wave motion

Implementation of other types of movement are still under development.

Another application that this system can be applied to is to be used as an end effector for a ABB robot as depicted in figure 8. If the robot that the snake is attached to also functions via the ROS system, the two system can be easily integrated into one another.

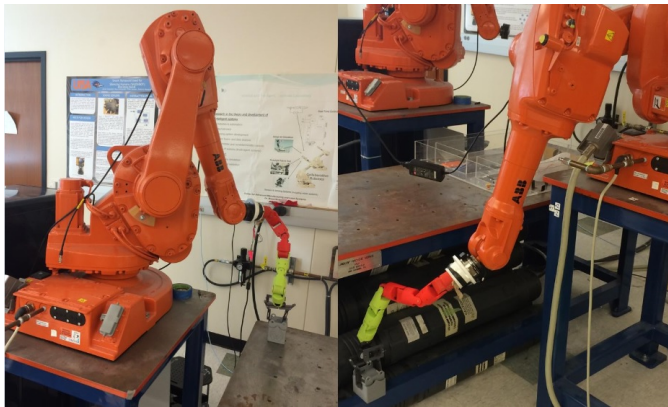


Fig. 8. Snake robot used as End effector for an Industrial Robot

VI. CONCLUSIONS AND FUTURE WORKS

In this paper a design for a 3D printed modular snake robot was presented which is low cost and was able to be constructed in a relatively short period of time. A control architecture for the snake robot has also been presented focusing on using a microcomputer to control the snake, with complex processing being undertaken outside the unit.

The implementation of all of the presented motions will be undertaken in the future, with the complete integration of the snake robot into a serial manipulator robot, as well as the robot to be integrated into a system of other robots to be investigated.

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