Snapbot: a Reconfigurable Legged Robot

Joohyung Kim, Alexander Alspach, and Katsu Yamane

Abstract— **We develop a reconfigurable legged robot, named Snapbot, to emulate configuration changes and various styles of legged locomotion. The body of Snapbot houses a microcontroller and a battery for untethered operation. The body also contains connections for communication and power to the modular legs. The legs can be attached to and detached from the body using magnetic mechanical couplings. In the center of this coupling, there is a multi-pin spring-loaded electrical connector that distributes power and transmits data between the controller and leg actuators. The locomotion algorithm is implemented on the microcontroller. The algorithm enables Snapbot to locomote in various configurations with one to six legs by recognizing configuration changes and selecting the locomotion method according to the current configuration. Snapbot will be utilized for further research on legged locomotion.**

I. INTRODUCTION

In nature, some creatures are able to change their number of limbs in various situations. Frogs grow two pairs of limbs and lose their tails during metamorphosis process from tadpole to adult. The starfish is able to separate a limb voluntarily to escape from a predator and regenerate it later. Many insects have six limbs but remain able to locomote after losing one or more. These examples are very different from one another but have one thing in common: The various creatures are adapting to their changing configurations in real time. In this work, we present a new robot named as Snapbot which adapts its locomotion pattern when reconfigured with combinations of multiple types of modular leg.

Legged robots and legged locomotion have been studied over past decades by many researchers. Among the multitude of legged robots, monopod, biped, quadruped and hexapod robots have been developed in the academic field and entertainment industry with great popularity [1]–[6]. Recently developed legged robots are able to walk, run, jump and perform manipulation tasks [7]. Most of these robots have adopted model-based control schemes to generate motions. This is a reasonable choice because it is assumed that the topology of a robot does not change while the robot is operating.

Alongside of legged robot research, some researchers have been studying modular robot systems and self-reconfiguring robot systems [8]–[12]. Modular robots are usually composed of multiple small-sized building block units with uniform coupling interfaces that allow transfer of mechanical forces, electrical power and communication throughout the robot. The modular robots often consist of some primary structural actuated unit and some additional units for specific tasks, such as grippers, wheels and sensors. In some studies on modular self-reconfigurable robots, locomotion of the modular robots, including legged locomotion, has been demonstrated.

Fig. 1. Snapbot can have up to six legs at a time. There are three types of magnetically coupled removable legs; six each. A locomotion algorithm determines the robot's configuration in real-time and chooses a combination of motions to propel the robot on a forward path.

There are also studies about changing or designing the topology of robot systems [13]–[15]. Bongard et al. [13] studied the ability to operate after injury by creating qualitatively different compensatory behaviors with a starfish-like robot. More recently, researchers have used machine learning techniques to developed robots that can adapt like animals when some part of the body is damaged [14].

These works are all related to our interest in emulating with robot systems the capabilities of legged creatures to undergo a configuration change and continue to locomote. Based on this motivation, we developed a reconfigurable legged robot, Snapbot, and experimentally tested its ability to locomote with varying configurations.

This paper is organized as follows. We first present a

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system overview of Snapbot. Section III reports the details of our robot's hardware focusing on its body, coupling mechanism and leg designs. In Sections IV, we present the locomotion algorithm of Snapbot and the actual implementation. Our conclusions and future work are discussed in Section V.

II. System Overview

Snapbot is a modular, reconfigurable robotic system. The system demonstrates motions for locomotion, environmental interaction and other tasks based on its various possible configurations. This system identifies its configuration using only internal sensors and utilizes a corresponding motion strategy to complete a task. The motion strategy changes as it is physically reconfigured in real-time.

A central component of Snapbot is the base unit, or body, which houses a controller and battery for untethered operation. The body of Snapbot features distributed electrical-mechanical connectors which locate, secure, power and communication with the modular legs. Mating connectors couple magnetically. An array of magnets restricts or allows certain orientations of leg attachment. In the center of this coupling is an 8-pin spring loaded electrical connector which connects power throughout the system and transmits data between the various actuators, sensors and the controller.

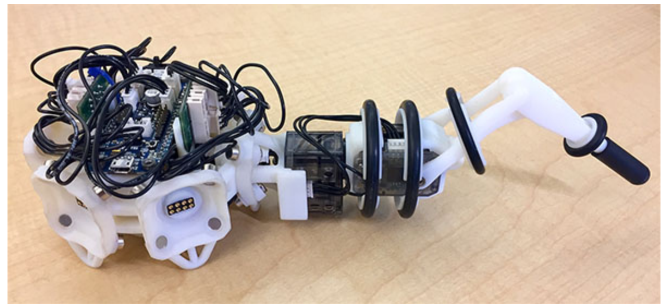
The motion controller determines the location and identity of attached components, which we refer to as the *configuration*, in real time by pinging all possible actuators and peripherals associated with the system. Based on the determined configuration, a combination of motions is executed to propel Snapbot on a path forward.

III. Hardware Design

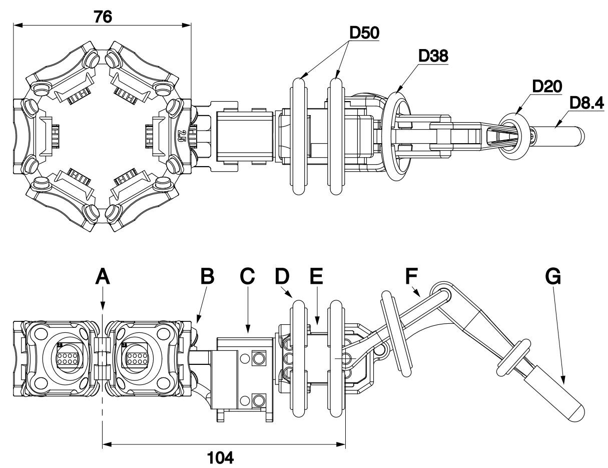
Snapbot consists of a 3D printed body and up to six legs which couple with the body magnetically. Fig. 2 depicts the body with one roll-pitch leg attached. Each leg features a magnetic mechanical coupling consisting of four magnets. In the center of this coupling, there is a pogo-pin electrical connector which transmits power and data between the body and attached components. In this section, the hardware design of Snapbot is described in detail.

A. Body Design

The body of Snapbot has a one-piece 3D printed frame structure. The body frame and all other 3D printed parts of Snapbot were printed on a Stratasys Objet260 Connex using VeroWhitePlus material [16]. On the top of the frame, there is a microcontroller and two 3-pin TTL hubs. The microcontroller is attached to the body frame with four commercial rivets. Under the controller board, there is space for a 7.2V, 800mAh lithium-ion battery. As shown on the bottom of the body frame in Fig. 2(a), there are six triangular support structures which minimize friction between the body and ground and keep Snapbot level to orient the attached legs. The body frame is shaped like a hexagon when viewed from above, as shown in Fig. 2(b). A leg coupling is located



(a) Snapbot Body and a Roll-Pitch Leg



(b) Drawings of Body and a Roll-Pitch Leg

Fig. 2. Snapbot consists of a body and up to six legs which connect in various planar configurations. The figure above depicts the body (A) with one leg attached. Each leg features a magnetic electrical-mechanical coupling (B), two to three position-controlled servos (C, E), and a 3D printed four-bar linkage (F) with rubber O-rings (D) and a rubber cap for friction (G) when locomoting. All units in (mm).

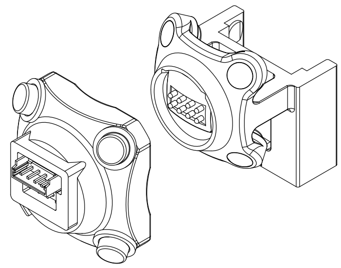
at each side of the hexagon. The detailed description of the coupling design is presented in the next subsection.

We use an OpenCM9.04 microcontroller board [17] for the locomotion control of Snapbot. The microcontroller connects to two hubs, and each hub connects to the three nearest couplings. This wired connection enables the Snapbot controller to send joint position commands to the coupling-connected servos of the attached legs. The communication period of Snapbot's controller in this paper is 20 ms.

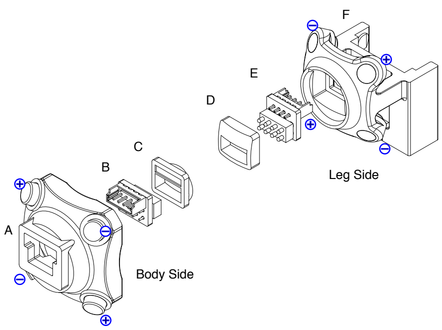
The design effort focuses on making the robot compact for efficient locomotion using a combination of off-the-shelf and 3D printed parts. The width of the hexagonal frame, side to side, is 76 mm, and the weight of body is 187 g including the battery and all electronic components.

B. Coupling Design

As described previously, the body of the robot features six couplings located around its circumference where legs can be attached. The coupling assembly, including the body- and leg-side components, can be seen in Fig. 3(a). Each of these coupling locations features four cylindrical (6.4 mm di-



(a) Assembled Coupling



(b) Exploded Coupling

Fig. 3. Shown above are the body- and leg-side coupling components. Each coupling component consists of a housing which mates with the companion coupling housing (A, F). Each coupling component contains an array of four magnets which restrict and allow certain configurations based on polarity, as labeled above. The leg-side component contains a spring-loaded 8-pin connector, PCB and 4-pin Molex connector (E), and the body-side contains a similar mating connector (B). Press fit caps are used to hold the electrical components in place (C, D).

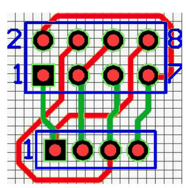


Fig. 4. The small PCB connects the coupling's electrical connector to the 4-pin connectors enabling power and data to transmit in two 180° offset configurations.

ameter, 6.4 mm height) neodymium magnets, each rated at a maximum of 26 N of pulling force. These four magnets are equally spaced around the perimeter of the connector in a square with alternating polarities, i.e. magnets situated diagonally from each other are facing the same direction, while the other two magnets face the opposite direction. The leg-side coupling features a complimentary magnet array which is attracted to the body when rotated to 0° and 180°, but repels at 90° and 270°.

Each coupling also features a spring-loaded electrical connector (coupling connector) which transmits power and provides two-way TTL communication with the leg servos when connected. The leg-side coupling houses the male connector, with eight spring-loaded pin contacts (2 pins × 4 pins), and the body-side coupling houses the the mating target connector, which has eight pads to contact the spring-loaded pins.

An exploded view of the coupling assembly components is depicted in Fig. 3(b). Each side of the coupling includes a 3D printed housing and geometry designed to mate with corresponding geometry on its companion coupling component. Each side of the coupling also includes seats for press-fit magnets oriented to pull normal to the coupling's spherical mating geometry. These magnets are aligned with corresponding magnets on the companion coupling component. The central spring-loaded coupling connector on the leg and the target connector on the body are each mounted to a small printed circuit board (PCB) which connects each of coupling connector's 8-pins to a Molex 4-pin connector. Wires connect the leg-side 4-pin coupling connection to the nearest servo while body-side wires connect the body coupling to the controller. The power and TTL connections between the controller and servos requires three pins total. The 2×4-pin coupling connector allows all eight pins make electrical contact in both attachment orientations (0° and 180°) allowed by the coupling.

The small PCB which connects power and data between the coupling connectors and 4-pin connectors is shown in Fig. 4. In each configuration, the power and data are transmitted by a different set of three pins. Therefore, the PCB connects each of the four pins on the 4-pin connector to two of the eight pins on the spring-loaded pin connector. For example, pin one (1) of the 4-pin connector is wired to pins one (1) and eight (8) on the spring-loaded pin connector, pin two (2) of the 4-pin connector is wired to pins three (3) and six (6) on the spring-loaded pin connector, etc. Because the power and TTL communication for the servos requires only three wires, the 4-pin configuration leaves one pin available for other data.

C. Leg Design

Snapbot is configurable with combinations of six or less legs. Each leg features a magnetic coupling (Fig. 3) with which it mechanically and electrically attaches to the body of the robot. We designed three different legs to emulate various legged locomotion styles. In Fig. 5, a roll-pitch leg is shown with detailed dimensions of the four-bar pitch mechanism. Fig. 6(a) and Fig. 6(b) show a yaw-pitch leg and a roll-yaw-pitch leg, respectively. These three leg types are selected because pitch motion is necessary to lift the end tip of the leg, and at least one more non-pitch DOF is needed to reach different points on the 2D ground plane. Each leg employs Dynamixel XL-320 position-controlled servos, one for each DOF. The servos are linked together via 3D printed components which snap to the servos for no-fastener assembly. The dimensions and components of the three legs are specified in Fig. 2, Fig. 5 and Fig. 6. The last DOF in each leg is a pitch DOF. The pitch servo, which is furthest from the body, drives a 3D printed four-bar linkage that converts the servo's rotational motion to a step-like trajectory. The linkage assembly of the four-bar mechanism and the interfaces to the

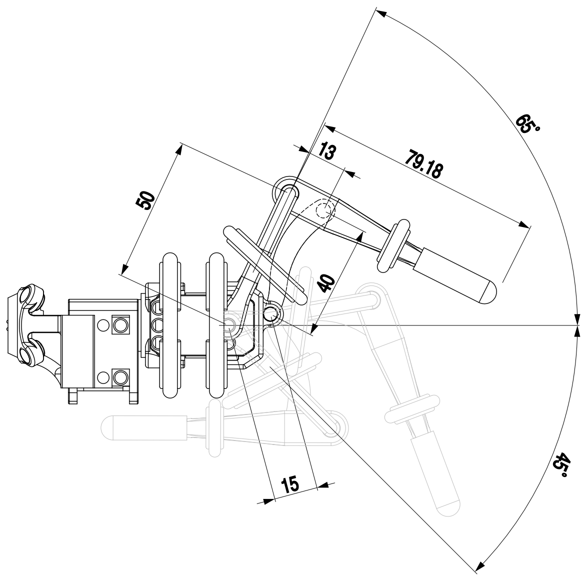
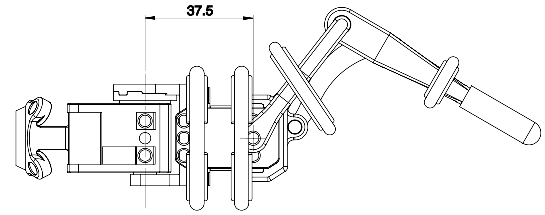
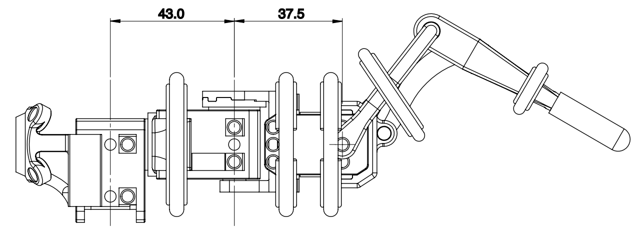


Fig. 5. Roll-Pitch Leg. Each leg has two to three position-controlled servos (roll, yaw, pitch) which are linked via snap-together 3D printed frame components. The four-bar linkage driven by the pitch servo creates a step-like foot trajectory. All units in (mm).



(a) Yaw-Pitch Leg



(b) Roll-Yaw-Pitch Leg

Fig. 6. Two more leg variations.

servo body and horn are 3D printed as a single articulating part which can not be disassembled. The range of motion of the actuated pitch joint in the four-bar mechanism is from -65°to 45°, as shown in Fig. 5. When the actuated servo is at 0°, the last link of the leg is perpendicular to the ground. When the angle of the servo is decreasing/increasing from 0°, the foot is lifting/folding inside. When the actuated servo is at 45°, the last link of the leg is fully folded, parallel to the leg link. The range of motion in the roll joint of both the roll-pitch leg and the roll-yaw-pitch leg is -150°to 150°. And the range of motion in the yaw joint of both the yaw-pitch leg and the roll-yaw-pitch leg is -70°to 70°.

The legs were designed with a focus on keeping them lightweight. However, where the structure of a 3D printed component is too thin, that area can be brittle and break easily. When moving, legged robots are exposed to the risk of impacts from collisions with the ground and other sources. To increase the impact resistance of the robot's structure, as well as increase the friction between the legs and the ground, rubber O-rings of varying sizes are situated along the length of the leg. There is also a rubber tip over the foot. With this design, Snapbot's legs are better able to endure the stresses and impacts associated with the various locomotion strategies introduced in this paper.

The mass of the roll-pitch leg, yaw-pitch leg and roll-yaw-pitch leg are 85 g, 87.5 g and 116 g, respectively. We built six of each type of leg for a total of 18 legs. With six of each, we are able to make a six-legged Snapbot with a single type of leg, as well as many other configuration combinations.

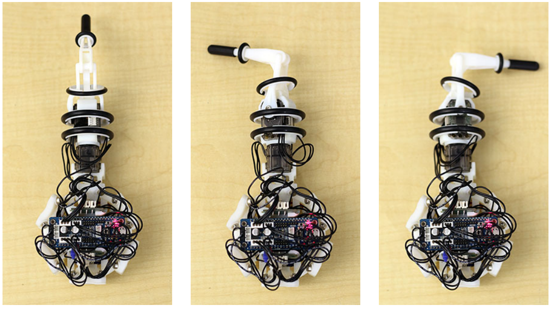
IV. Locomotion Algorithm

The locomotion algorithm is implemented on the controller board of the robot's body. The locomotion algorithm is composed of two parts: recognition of Snapbot's current configuration and its motion control. In this implementation, the goal task of Snapbot was limited to traveling straight forward.

A. Self Recognition of Configuration

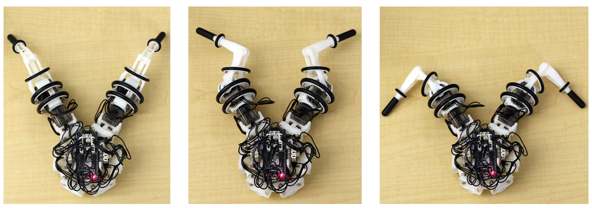
Snapbot's configuration can be changed by snapping and unsnapping legs from the couplings. The robot needs to know its current leg configuration in order to decide how to locomote with said configuration. Using only one type of leg, there are 14 different combinations of leg configuration, including that with no legs, as shown in Table I. With three types of legs, the total number of combinations is 700. The self recognition step determines in real time which configuration among Snapbot's 700 possible configurations is the current configuration.

In the self recognition layer, the controller checks its configuration periodically. It is possible for the robot to determine its configuration by pinging motors IDs and by monitoring for a connected signal on reserved pins in the coupling connector. Each modular leg has servos with specific IDs and, by pinging the ID numbers (scanning), the robot can tell which leg is attached. To determine where a leg is attached, a pin in the connector connects a servo data line to the controller's analog to digital converter. The signal on this pin is used to determine whether or not a leg is connected to a given port. Using this information, the robot is able to recognize its configuration, that is, which leg is connected to which port. Currently, Snapbot checks its configuration every 100 ms.



(a) Neutral pose (b) Rowing left (c) Rowing right

Fig. 7. Rowing Motion



(a) Neutral pose (b) Streching legs (c) Pulling legs

Fig. 8. Crawling Motion

B. Motion Control

Once Snapbot recognizes its configuration, it decides how to locomote based on the task and controls its actuators accordingly. In this paper, the locomotion patterns are combinations of three basic motions. These basic motions include a rowing motion, crawling motion and walking motion. When Snapbot is rowing or crawling, the body is dragged on the ground. While walking, Snapbot's body is raised off the ground with each foot having only a point contact with the ground. The trajectories of the basic motions are predetermined through experiments and hard-coded depending on configuration.

1) Rowing Motion: The rowing motion in Fig. 7 is used only for the single-leg configuration. Using one leg, Snapbot pushes on one side then lifts the leg and rotates to push on the other side, like rowing a canoe, to generate a backward frictional force between the ground and the tip of the leg.

2) Crawling Motion: Crawling is a motion which uses the symmetric motion of two legs simultaneously. Figure 8 shows the crawling motion when two modular legs are attached adjacent to one another. The crawling motion can be used in all three cases of possible two-leg configuration shown in Table I. The motions for configurations with three legs or more can be implemented with a combination of crawling motions.

For the crawling and rowing motions, the roll joint movement is effective because it is able to increase the contact area between the rubber foot and the ground by changing the orientation of the pitch joint. Therefore, roll-pitch legs and roll-yaw-pitch legs are better than yaw-pitch legs when rowing and crawling.

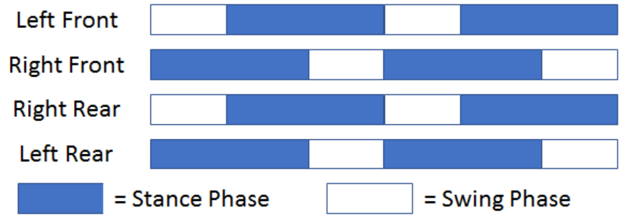


Fig. 9. Ground contact visualization of two walking cycles in trot gait

3) Walking Motion: In this paper, a locomotion controller is implemented for a limited number of configurations. Snapbot is able to walk when the following conditions are satisfied.

(a) The attached leg configuration should be one of the following three configurations shown in Table I: The four-leg 'X' configuration (09), five-leg configuration (12) or six-leg configuration (13).
(b) Any combination of two and three DOF legs can be attached at a time as long as roll-pitch and yaw-pitch legs are not used together.

The implemented walking pattern is similar to a trot gait, using its legs in unison in diagonal pairs. The condition (a) is necessary because diagonal pairs are needed for a trot gait. Condition (b) arises due to differences in motion trajectories of roll-pitch and yaw-pitch legs. Each of these legs has a motion that the other can not reproduce which makes it difficult to execute a trot when used together. Because the 3DOF roll-yaw-pitch leg can replicate the motion of either 2DOF leg, combinations of roll-pitch and roll-yaw-pitch can be used, as can combinations of yaw-pitch and roll-yaw-pitch.

Figure 9 shows the ground contact timing of four legs while trotting. During the swing phase, the swing legs lift and advance to make a step. The stance legs propel the body moving the center of mass forward. Snapbot's trot is implemented by repeating this motion periodically, alternating between left and right. In Fig. 10, a series of photos of Snapbot's trot are shown. The Snapbot in Fig. 10 has four yaw-pitch legs. The pictures were taken every 0.1 sec and the direction of Snapbot movement in the photos is up. In the first picture (top left), Snapbot lifts the right-front leg and left-rear leg. In the third picture, the two raised legs were move forward while the two stance legs move the body forward.

In the case of a five-leg configuration, Snapbot trots if the above conditions are met and moves in the direction of the fifth. The fifth leg is raised in the air and held still. If these conditions are not satisfied, Snapbot decides to crawl for locomotion even with more than four legs.

In a six-leg configuration, the four side legs execute a trotting gait while the other two legs help to propel the body using the pitch joints. The goal direction is decided based on the the above conditions and based on joint ID number (in the direction of lowest numbered servos).

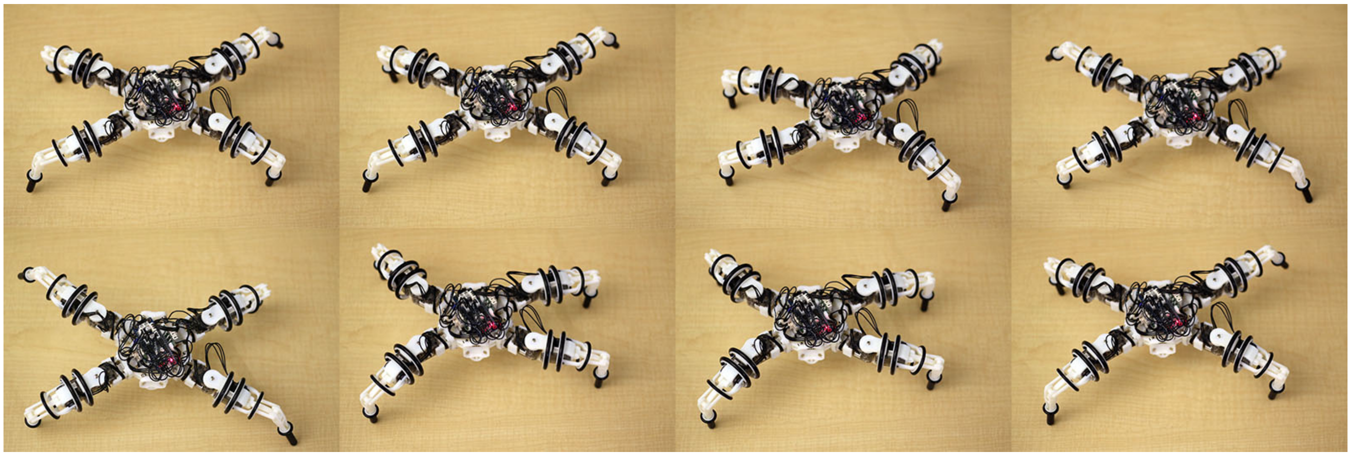


Fig. 10. Series of pictures of four legged walking. Snapbot is moving towards the top of the page (upward) using a trot gait. All attached legs are yaw-pitch legs. Pictures were taken every 0.1 sec and the order is from left to right, top to bottom.

V. CONCLUSION AND FUTURE WORK

The goal of this work was developing a robotic system to emulate the capabilities of legged creatures, which can undergo a configuration change and continue to locomote. For this goal, we designed Snapbot, a reconfigurable robot which accommodated 0 to 6 modular legs and decided how to locomote based on this configuration. We designed a 3D printed body which housed a microcontroller and a battery and contained connections for communication and power to the modular legs. The modular leg was designed with a magnetic mechanical coupling and a multi-pin spring loaded electrical connector which distributes power throughout the system and transmits data. We designed 3 kinds of legs with 2DOF or 3DOF to have various configurations. As the result, Snapbot could have 700 different configurations and recognize the current configuration. Snapbot was tested experimentally and was was able to locomote with various configurations.

We are planning to make Snapbot learn how to locomote using reinforcement learning or evolutionary algorithms. For this, other sensors including a camera will be attached either to Snapbot or externally.

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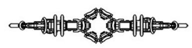
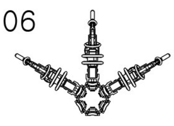
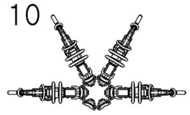
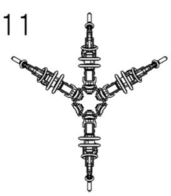
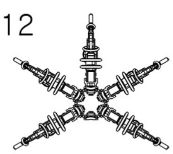
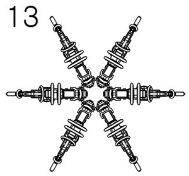
Configurations	Locomotion
01 	• One configuration • Rowing
02  03  04 	• Three configurations • Crawling with two limbs
05  06  07  08 	• Four configurations • Crawling with two limbs, not using the other
09  10  11 	• Three configurations • Walking with four limbs (first configuration) • Crawling with two limbs or two pairs of limbs
12 	• One configuration • Crawling with two pairs of limbs • Walking with four limbs
13 	• One configuration • Walking with six limbs • Crawling in various ways

TABLE I

CONFIGURATIONS AND LOCOMOTION STYLE