Docking Among Independent and Autonomous CONRO Self-Reconfigurable Robots

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Abstract— **Docking between independent groups of self-reconfigurable robotic modules enables the merger of two or more independent self-reconfigurable robots. This ability allows independent reconfigurable robots in the same environment to join together to complete a task that would otherwise not be possible with the individual robots prior to merging. The challenges for this task include (1) coordinate and align two independent self-reconfigurable robots using the docking guidance system available only at the connectors of the docking modules; (2) overcome the inevitable errors in the alignment by a novel and coordinated movements from both docking ends; (3) ensure the secure connection at the end of docking; (4) switch configuration and let modules to discover the changes and new connections so that the two docked robots will move as a single coherent robot. We have developed methods for overcome these challenging problems and accomplished for the first time an actual docking between two independent CONRO robots each with multiple modules.**

Keywords*- self-reconfigurable robots, autonomous docking, remote sensor alignement, compliant docking.*

I. INTRODUCTION

Docking between multiple components is a basic problem that occurs in almost all engineering systems that must dynamically change their structures for various purposes. Generally speaking, docking behavior can be either human-operated or autonomous.

Human-operated docking is widely seen in daily life, and can be as simple as changing a blade in a razor or as complex as docking one spacecraft to another. One example of human-operated docking is docking the space shuttle to an orbiting craft. Here docking has to be very precise and the procedure can be lengthy. It can take hours to accomplish space docking under human master-slave control. The position and attitude requirements are very severe since the opening is large and the joint has to be good enough to support an airlock. Thus, not only is it necessary to control the position and orientation, but the force needed to compress the o-ring seal must be controlled correctly also, thus adding complexity to the task.

In comparison with human-operated docking, autonomous docking is a more difficult problem. For example, two satellites docking in space may take many hours to align, approach, dock and secure. In many engineering domains, conditions are preset in order to make the process feasible and reliable. For example, docking among locomotives and railroad cars is an example worth looking at in detail. The cars are on rails; all rails in one country have the same width (to quite high tolerances); all cars have the same height (again to quite high tolerances); the coupling hooks are genderless (hermaphroditic) and held loosely enough so that the hook on one car will slide over the hook on the second car in spite of the build-up of tolerances and then lock. Under these conditions, docking can happen automatically when two railroad cars are approaching each other on the same track with a certain speed. After docking is established, the locomotive then pulls the train of cars. No precision is required in pulling -- just pure tension. Nor is precision required in moving in reverse -- the train is constrained by the track. Under these circumstances, a simple symmetric hook linkage is sufficient for docking. Of course, simplicity is an after-the-fact observation. The actual dock that is employed is a major technical accomplishment from the era of the railroad.

Among all applications of autonomous docking, perhaps the one that demands autonomous docking the most is the self-reconfigurable or metamorphic robot. Such robots are made of many autonomous modules that can self-rearrange their connections to change the robot's morphology (e.g., shape and size) in order to meet the environmental and other demands of a given task. Such robots are useful in applications that benefit from or require the use of robots with different topologies.

Docking in self-reconfigurable robots can be divided into two classes: intra-robot docking, which addresses the problem of docking among modules that are in the same connected group, and inter-robot docking, which deals with docking between two independent and unconnected groups of modules. The examples of intra-robot docking include the water-flow movement of lattice-based self-reconfigurable robots [10, 11], a chain-based "crab" robot morphs into a "snake", a "ball", or a "gripper". Examples of inter-robot docking include situations where one self-reconfigurable robot disassemble itself into a set of independent and autonomous agile units to spread out in a large area, and later reassembly them back into a single robot.

Previous research in docking for self-reconfigurable robots has been focused on intra-robot docking. Examples of such docking include a CONRO snake robot docking its tail into its head [1], a Polybot snake changing into a quadruped [4]. Most recently, MTRAN robot [11] has demonstrated many impressive intra-robot reconfigurations. For lattice-based self-reconfigurable robots, docking has been demonstrated in simulation for many years, and the most recent theoretical result has been reported by [10]. However, docking in lattice-based robots is mostly intra-robot and requires modules to be already connected in an existing group and occupy at pre-oriented grid space. For mobile (wheeled) robots with docking connectors, Bereton and Khosla [7] have used visual images as guidance for docking between separate mobile robots. Their docking connector has a forklift and a receptacle and allows approximately 30-degree alignment errors. Their robots are skid-steered, i.e., when the forklift pins are partially in the receptacle and the robot pushes straight ahead, the wheels of the robots slip on the ground and allow the robot to center the pins in the receptacle. This feature, however, is not generally available for modular self-reconfigurable robots. In addition, docking among self-reconfigurable robots typically involves many connected autonomous modules in each robot.

The task of inter-robot docking is similar to the task of intra-robot docking, however there are several main difficulties that are unique for independent inter-robots docking. First, in the case of independent CONRO robots, they must use the same sensors for both communication and alignment, whereas in the case of docking for single robot reconfiguration, the communication had an existing pathway through the robot itself. The second difference is that the general alignment of the docking heads in intra-robot docking is known based on the positions of all the modules in the robot, while in the inter-robot docking, the robots start with no prior knowledge of the other's position or alignment, and their movement must be coordinated by sharing relative positions among the two docking modules. Additional difficulties for inter-robot docking include (1) the coordination and alignment of two independent self-reconfigurable robots must rely on the docking guidance system available only at the connectors of the docking modules; (2) overcome the inevitable errors in the alignment by a novel and coordinated movements from both docking ends; (3) ensure the secure connection at the end of docking; (4) switch configuration and allow modules to discover the changes and new connections so that the two docked parts will move as a single coherent robot.

A difficulty using CONRO in this task is that the infrared sensors provide limited information about the position and orientation of the two docking robots. The only information that can be obtained by using one infrared sensor is the approximate direction to the brightest infrared source. With the current sensor configuration of CONRO, a simple robot can only tell the relative incoming angle of infrared light, but cannot determine the absolute orientation of the transmitter. This means that one CONRO robot cannot determine the orientation of another independent CONRO robot directly. This limitation makes the act of docking by independent CONRO modules difficult.

This paper will use CONRO robot [6,8,9] http://www.isi.edu/robots/ (then click "conro") as a platform for intra-group docking. Since the task of autonomous docking in such a robot is so intricate and challenging that if a reliable solution is identified here, it could be applied to almost any docking domain.

The paper is organized as follows. Section II describes the docking mechanism and guidance system in CONRO, Section III and IV describes our open-loop and close-loop approaches to inter-robot docking and experimental settings. Section V discusses the implications of this algorithm. VI describes the results of the experiments. Section VII describes future work based on this algorithm.

II. CONRO DOCKING/GUIDANCE HARDWARE

The CONRO self-reconfigurable robots are made of a set of connectable, autonomous, and self-sufficient modules. Illustrated in Figure 1, each module has, one micro-processor, two motors, four docking connectors for connecting with other modules, and four pairs of infrared emitter/receiver for communicating and sensing other modules. Some modules are also equipped with other miscellaneous sensors such as tilt sensors and miniature cameras. More information and movies of CONRO can be found at http://www.isi.edu/robots.

Each CONRO module has two degrees of freedom: DOF1 for pitch (up and down) and DOF2 for yaw (east and west). Each DOF has a home position (when the joint is straight), and has two joint limits (when the joint reaches the maximal or the minimal angle). With these two DOFs, one or more connected modules can perform locomotion with coordinated actions.

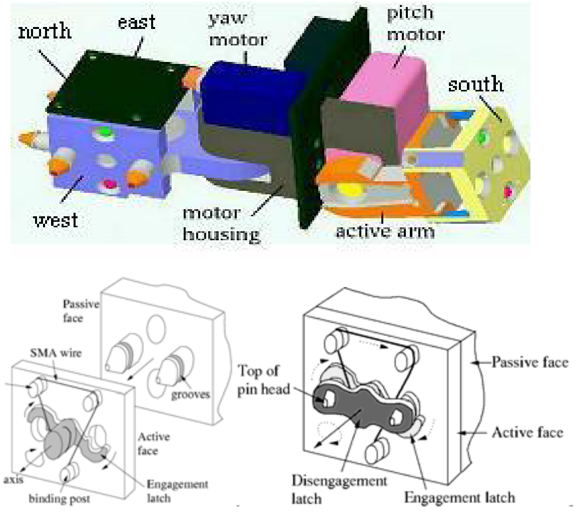

Figure 1. A single CONRO module and the connectors for Docking and De-Docking between CONRO Modules

CONRO modules can connect to each other by their docking connectors located at either ends of a module. At one end, three male connectors are located at the three sides of the module (shown as North, East, and West in Figure 1), each of which consists of two docking pins. At the other end, a female connector is located at the tip end of a module (shown as South in Figure 1), which consists of two holes for accepting other module's docking pins. This female connector has a locking/releasing mechanism behind the holes, and can have two states. In the default or non-active state, it can accept and lock the incoming pins by a spring motion. In the activated state, it can release the lock by triggering a SMA actuator. The connector/releasing mechanism is power efficient and it consumes no electric energy when in the default state. For detailed design and implementation of these docking connectors, please refer to [5].

The details of the docking system in CONRO are also shown at the bottom part in Figure 1. Each module, with its docking connector, was designed to accommodate five sets of pairs of pins at one end, two horizontal, two vertical and one straight ahead, and one set of a pair of docking holes at the other. Only three sets of pins were incorporated in the prototype shown, for reasons of cost and mechanical complexity. The group consisting of North, West, and East (see Figure 1) was chosen since they form a plane. The connectors are keyed to allow connection in only one orientation, again for simplicity. This arrangement allows a module to be connected to four (out of a possible six) other modules, front, back and two sides in order to make chains, trees, and other structures. The docking pins in the passive connectors are chamfered, and in operation they enter chamfered docking holes in the active connector and slide to the full depth, at which point they are locked in place by a spring loaded lock.

The system was designed to be capable of self-reconfiguration and thus needs to support disconnection; both connection and disconnection are fundamental to physical reconfiguration. A shape memory alloy (SMA) system in the active end of the module is used to release the spring-loaded lock in a selected module so that the robot can pull itself apart at the released joint for automatic disconnection from its neighbor [1,2,6]. This can be used either for the reconfiguration of good, operating modules or for shedding defective modules. Through these connectors, a specific, physical, robot morphology can be constructed from a large but finite set of possible arrangements by the suitable interconnection of modules. The normal mode of operation of a metamorphic robot is to connect the basic modules together to create a starting configuration and then allow the system to run autonomously, and to morph as needed, and even performing an automatic fusion or field merge with another CONRO.

Controlling each module is a Parallax BASIC Stamp 2 SX chip, which is based on the Microchip PIC micro-controller and the Parallax Stamp BASIC interpreter. To control the servos, a FT639 servo driver chip receives updated messages from the Stamp, and continuously drives the servos through standard pulse-width modulated signals. This was chosen as it both relieves the Stamp of continuously generating the PWM, and it moves the higher currents of driving the servos off of the main PCB.

The infrared emitter/receivers located in the docking face can be used as sensors for guiding two modules to align each other during a docking action. When two modules are in the range of the infrared signals, they can measure the strength of the received the signal and use the measurements to estimate the quality of the alignment between the two modules.

A group of many modules can apply various gaits to the system for locomotion, depending on the current configuration. In a linear "snake" configuration alone, there are many sidewinder and caterpillar gaits from which to choose. In a legged configuration, like the quadruped, hexapod, and *n*-ped configurations, there are also many different styles of motion. For example, if the central spine remains rigid, then an insect-like gait can be used. If the spine bends regularly, then a more "lizard-like" gait is observed. Both of these kinds of gaits have been successfully implemented on the CONRO system.

III. OPEN LOOP DOCKING EXPERIMENT

The task of docking two independent self-reconfigurable robots is first done in open loop (without sensor feedback) to verify the movements and communication used for docking are correct. The independent robots consist of two modules each. These modules are connected head to tail to form a snake. For reference, the CONRO modules will be named from left to right according to Figure 2, so the left most CONRO module in Figure 2 is module one, the next module to the right is module two, and so on. Snake A consists of modules one and two. They are docked to each other at the south female connecter of module one and the north male connecter of module two. Module one and two can communicate to each other using the infrared emitters and receivers at the docking point between module one and module two. Snake B consists of modules three and four. They are docked to each other at the south female connector of module three and the north male connector of module four. Module three and four can communicate to each other using the infrared emitters and receivers at the docking point between module three and module four.

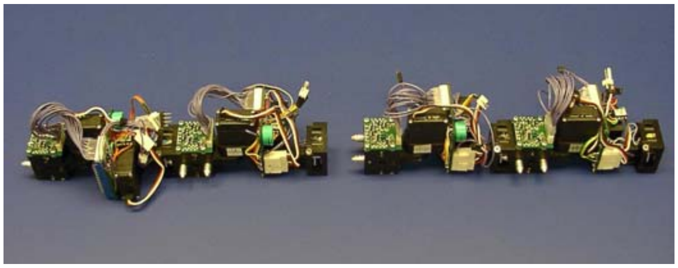

Figure 2. Initial configuration for open loop experiment.

For the snakes to dock, the north male pins of module three in snake B must move directly into the south female connector of module two in snake A. This movement must be orthogonal to the face of the female connector due to the fact that the docking will only occur when the male pins are completely submerged into the female connector. This constrains the type of movements that can be used to dock the two snakes together. During the process of docking, snake A does not change position. The only movement from snake A during docking is a gentle vibration of the pitch axis of module two to provide a dynamic lubrication. The docking movement for snake B involves moving the pitch arm for both modules three and four in a way that keeps the northern male connector of module three orthogonal to the face of the south female connector on module two, while at the same time, moving towards snake A. Using angles and distances marked in Figure 3, where θ_1 is controlled by the pitch motor in module three, and θ_2 is controlled by the pitch motor in module four, if module three freely moves θ_1, then θ_2 must move according to the formula (1) to keep the pins of module three orientated properly for docking.

$$\theta_2 = \mathrm{Sin}^{-1}((L1/L2) \mathrm{Sin} (\theta_1)) \qquad (1)$$

If θ_1 slowly changes to 40 degrees, slowly changes back to zero degrees, and repeats while θ_2 is moved according to formula (1), snake B should move in the direction of snake A, keeping the northern male connector on module three properly oriented for docking.

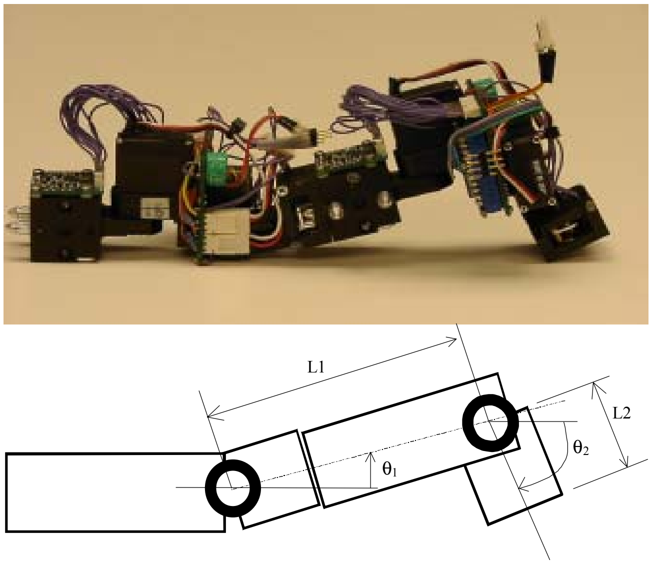

Figure 3. Docking movement and corresponding diagram for snake B

The two snakes are placed in the proper orientation to each other to allow docking using the docking movements. This orientation, shown in Figure 2, places the south female end of module two in snake A into the proper docking orientation to the north male end of module three in snake B.

The open loop docking experiment consists of two phases. The first phase is before the docking has occurred. During this phase snake A and snake B are executing their docking movements. During phase one, module three turns on its infrared transmitter in its north end, while module two is monitoring the infrared receiver on its south end. Module one is monitoring its south infrared receiver awaiting module two to turn on its north infrared transmitter, signaling that docking is complete. Module three is monitoring its north infrared receiver awaiting module two to turn on its south infrared transmitter, signaling that docking is complete. Module four is monitoring its north infrared receiver awaiting module three to turn on its south infrared transmitter, signaling that docking is complete. Once module two detects that the brightness of module three's north infrared led crosses a pre-set threshold, module two considers itself docked. At this point, the experiment transitions to phase two. During phase two, a signal that docking is complete is propagated to the remaining three modules. Module two propagates this signal by turning on its north and south infrared transmitters. Once module three detects module two's infrared transmitter, it relays the message to module four by turning on its south infrared receiver. At this point, all four individual CONRO modules realize that they are docked, and may move and communicate like a single CONRO robot composed of four modules.

IV. CLOSED LOOP DOCKING EXPERIMENT

The closed loop (using feedback from sensor data) docking experiment starts with a configuration that has the two snakes generally facing each other, but misaligned by up to 45 degrees and separated by up to 15 centimeters. The misalignment should not be greater than 45 degrees due to the fact that the snakes may not be able to sense the others infrared emitter, which is required in the first phase of this experiment. An example starting configuration is shown in Figure 4.

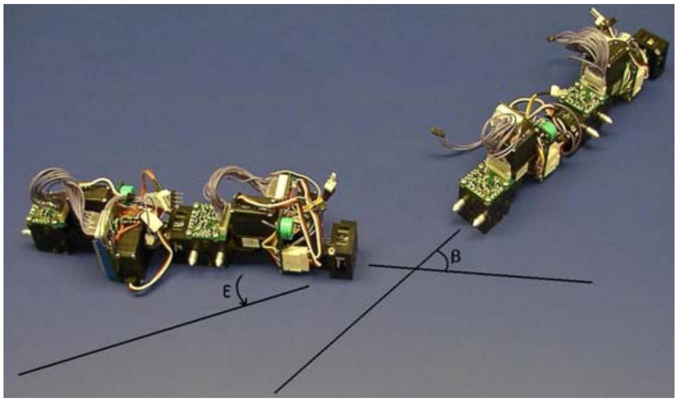

Figure 4. Closed loop experiment starting configuration

The two snakes have unique movements that allow them to align towards the other snake. Different from the open loop experiment where only Snake B moved, both Snake A and B must change their orientations here to align. The movement that snake A implements to align itself uses the south infrared sensor of module two to determine the infrared intensity coming from the north infrared emitter of module three. Module two then communicates to module one which direction it wants to rotate. Module one rotates snake A ε degrees in the desired direction, using a combination of pitch and yaw movements. This type of movement was labeled as "around the internal signal" in [1]. This rotation is done about the south connector of module two. Once this rotation is complete, module two re-samples its south infrared receiver, and if the value is greater than the previous value, it sends a signal to module one to rotate ε degrees in the same direction as before. If the value that module two re-samples is less than the previous value, it sends a signal to module one to rotate ε degrees in the opposite direction than the previous rotation. It then repeats this process a preset number of times. Every time snake A changes the direction that it rotates, it decreases the value of ε. This decrease in ε allows for a quicker convergence to the desired orientation with respect to snake B. Using this approach, snake A will aim the south end of module two towards the north end of module three in snake B.

The method snake B uses to align itself towards module two's infrared emitter on its south end is slightly different from the method snake A uses. Snake B rotates the yaw axis of module three ± 45 degrees from its centered position, and finds the direction of greatest infrared intensity. It then uses module three to rotate snake B about the south connector of module four (this is called "rotating around the joint" in [1]), using a combination of pitch and yaw movements. It attempts to point the north connector of module three in snake B towards the source of infrared light from module two in snake A. It repeats this until the snake is pointing in the direction of greatest infrared intensity. Using this approach, snake B will aim the north end of module three towards the south end of module two in snake A.

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Phase I

Align snake B to the transmitter in snake A

Phase II
Align snake A to the transmitter in snake B

Phase III
While(Ir. intensity snake B receives from snake A < Preset
        threshold)
             align snake B to the transmitter in snake A
             move snake B towards snake A

Phase IV
While(docked == false)
             run docking movement for both snakes

Phase V
Transmit docked signal to all modules
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Figure 5. Generalized implementation alignment and docking

The closed loop docking experiment consists of five phases. The generalized implementation of alignment and docking is shown in figure 5. Figure 6 shows the closed loop docking process used in this experiment. The first phase consists of snake A emitting infrared light from the south end of module two. Snake B then uses its method of aligning its north end to the direction of greatest infrared intensity. Once the aligning process of snake B is finished, the process moves on to phase II. In this phase, module three turns on its north infrared emitter, and pauses its movement. Snake A detects this, and turns off its infrared emitter. Snake A then proceeds with it's method to point the south end of module two towards the brightest infrared source. When snake A is aligned, it activates the infrared emitter on the south end of module two, signaling the end of phase II. Snake B detects this, and turns off its infrared emitter. In phase III, snake B first aligns its north end towards the brightest infrared source. At this point, the alignment error angle β is within docking tolerance. Snake B then alternates between moving forward and checking alignment. This pattern of movements is to ensure that the forward movement does not alter the alignment. Phase III completes when snake B detects the infrared intensity reach a preset threshold. Phase IV starts with snake B signaling snake A to move to the new Phase. The snake configuration at the start of phase IV is the same as the configuration at the start of the open loop experiment, so phase four and five in the closed loop experiment are identical to phase one and two in the open loop experiment. Therefore, like the open loop experiment, the closed loop should conclude with the two snakes joined together moving and communicating as a single CONRO robot composed of four modules.

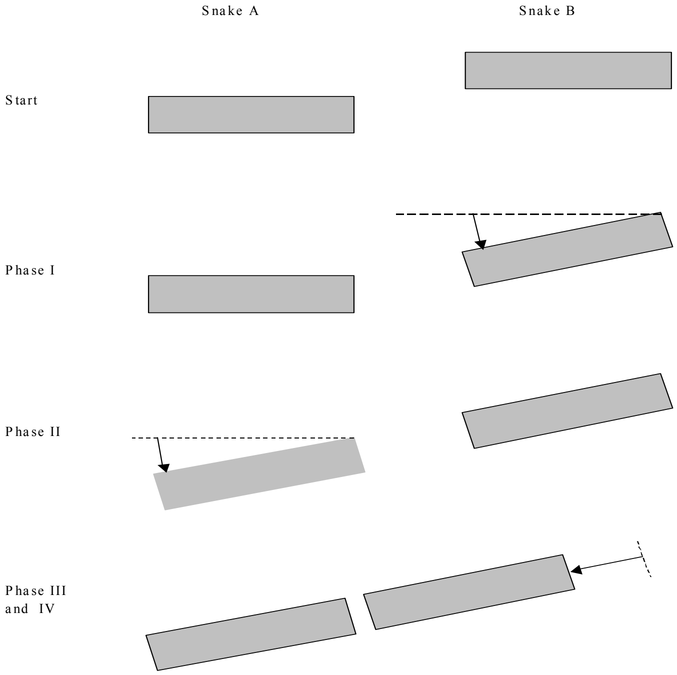

Figure 6: Closed-loop docking process

V. DISCUSSIONS

While the separate robot docking experiments work well, the same alignment algorithm can also be used to aid in docking for single robots during reconfiguration. Autonomous docking is extremely critical for the success of metamorphic robots. Without a reliable solution to this problem, the true advantages of metamorphic robots cannot be delivered to real-world applications and will remain a mathematical exercise exciting only scientific curiosity. After nearly ten years of research by the international community, autonomous docking is commonly believed to be the most challenging problem in self-reconfigurable robots. The challenge lies in the fact that autonomous docking is the only ability that enables all reconfigurable actions, and it must be performed frequently and in different system configurations. Such docking systems involve positioning the various modules correctly, then making a connection that must support as many modalities as needed in a particular application, and work in many hostile environments

The use of infrared sensors to aid in docking had been done before. Yim et al. [3] was able to determine exact position and orientation of connectors using four infrared transmitters and two infrared receivers on each of the docking connectors. In our experiment, there is only one transmitter and one sensor that is actively used for guidance in each CONRO snake. This limitation does not allow the CONRO snakes to sense the orientation of the other snake, only its direction. Even with this limitation, the alignment algorithm used allows the snakes to align and dock automatically in up to five degrees of freedom. This reduction in the number of sensors needed for docking can help keep the complexity of the modules to a minimum.

VI. EXPERIMENTAL RESULTS AND CONCLUSIONS

Both the open loop experiment and the closed loop experiments successfully docked the two snakes together. Videos of both experiments are available at www.isi.edu/robots/movies. These experiments were successfully repeated on carpeting. Docking was successful for all ten runs of the experiment. Each experiment lasts about 5-10 minutes depending on the initial position and orientations. This shows that our docking method is of high reliability.

This experiment could easily be adapted to allow docking of two separate snakes each containing greater than two modules. The general alignment algorithm used could also be applied to robots with a shape other than a snake. This work shows that even the simplest groups of self-reconfigurable robots are capable of merging into a single robot.

VII. FUTURE WORK

Now that the merger of separate reconfigurable robots is possible, in our future work we can try to apply this alignment algorithm towards reconfiguration of a single robot. We will also try the docking in more challenging environment such as pebble or sand commonly found on the coastlines and other difficult environments.

ACKNOWLEDGMENT

We are grateful that this research is sponsored by AFOSR under award numbers F49620-01-1-0020 and F49620-01-1-0441. We also want to thank other members in the Polymorphic Robotics Laboratory for their generous intellectual support and discussions.

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