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A System for In-Space Assembly

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Abstract— **This paper presents an experimental system for assembly in space. A weightless and frictionless environment is approximated using an air-hockey table where robots and structural components can float on the surface. The robots use fan propulsion to dock with components and assemble them together to make 2D structures. This system is designed to implement three key technologies for space self-assembly: 1) intelligent components with universal connectors, 2) a set of self-reconfigurable robots that fetch and assemble components, and 3) a distributed method for controlling the robotic-assembly process. An overview of the system's design and experimental results is presented.**

Keywords-component; assembly, self-reconfiguration, space robot

I. INTRODUCTION

Assembly is the process of using robots, robotic modules, intelligent or non-intelligent components to make larger complex structures automatically. This differs from industrial robots on assembly lines which require on-site engineers, precise calibration, and controlled environments. True robotic-assembly occurs in-situ, without the intervention of humans, and in uncontrolled environments. Calibration and configuration is autonomous, and the system is tolerant to failures in hardware or hazards in the environment.

Future structures in space are likely to be big and complex (e.g., a typical solar power system would have many thousands of components). Assembly performed by astronauts would be too expensive and risky. We believe that a robotic-assembly technique provides a cost-effective alternative and is now within the reach of today's technology.

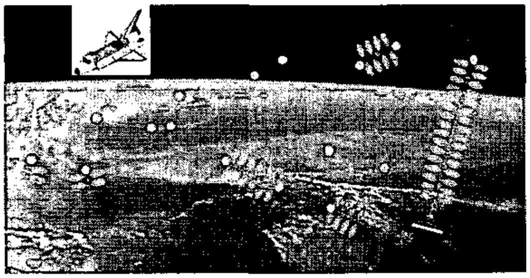

Figure 1. In-Space Assembly Using FIMER Robots.

Our approach to assembly in space is based on the technologies developed for self-reconfigurable robots [7,8]. We envision making each structural component able to dock[3,9] and assemble with assistance of a set of free-flying match-maker robots called FIMERs. A conceptual vision of the FIMER robots in action can be seen in Figure 1.

The objects with multiple disks are components to be assembled. Components are connected to each other using a set of connectors. All connectors are canonically designed so that any two connectors can dock or de-dock at will.

As we described in [7], the string-like objects are the FIMER robots. Each FIMER robot is a pair of free-flying "heads" tethered by a thin fiber that can be reeled in and out by the heads. (Other use of tether in space robotics can be found in [5].) Each head can fly autonomously and can communicate with and dock/de-dock with any component or other FIMER robot. The two heads in the same robot can fly away from each other (as far as the tethered line allows), and they can pull each other by reeling in the tether. When the two heads are attached to two different components/structures, a FIMER robot can pull the two parts together and assemble them together. The control and navigation of the FIMER robots is much simpler than a free-flying approach because of the tether and the ability to attach to other structures.

We have designed a prototype of a FIMER robot and conducted some successful self-assembly operations that validate our approach. We present our results below.

This paper is organized as follows. Section II explains our self-assembly strategy. Section III gives an overview of our space-like experimental environment. Section IV describes our experiments. Section V discusses the results. Section VI concludes the paper and outlines future work.

II. ROBOTIC-ASSEMBLY STRATEGY

To validate our approach, we have selected an equilateral triangle composed of three homogeneous beams as a simple structure to build through in-space robotic-assembly. This can be generalized to truss assembly in the future. We intentionally chose a two-dimensional structure to give us the ability to perform experiments in earth gravity.

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We have composed an assembly sequence for building triangles using a single FIMER robot. Our approach is to experimentally verify each step individually first with our prototype then string these steps together in a single behavior. The assembly sequence can be seen in Figure 2.

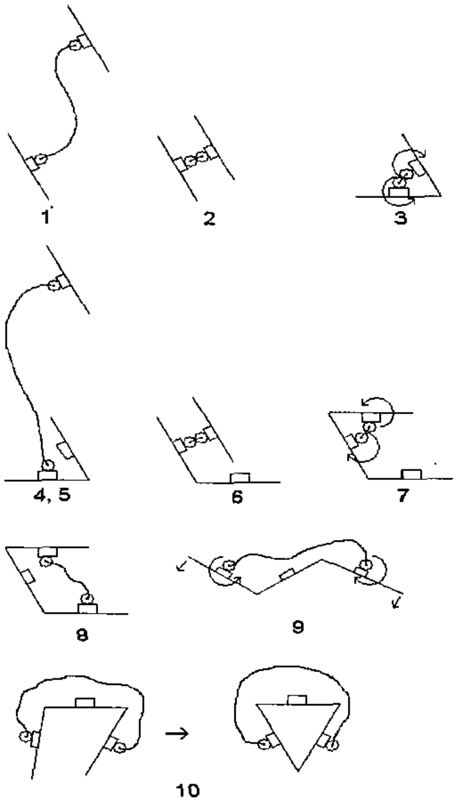

Figure 2. Triangle Assembly Process.

We call a FIMER head a Puck. An assembly process will begin by a FIMER flying and connecting its two Pucks to the connectors of two beams. Once the Pucks are attached to the beams, the two Pucks will pull the beams together by reeling in the tethered line until the two Pucks touch each other. They will then rotate themselves so that the ends of two beams will touch and connect. After the connection is made, the Pucks can fly away for other tasks. Four primitive actions are needed to perform the above process, and they are Go-Get, Reel-In, Mirror-Roll, and Guide-In, described below:

The Go-Get Behavior: This behavior utilizes a seek-and-avoid algorithm that allows a Puck to go and dock with a beam. The Puck docks perpendicular to the center of the beam.

The Reel-In Behavior: Once a beam has docked with the Puck, the Reel-In behavior pulls the two Pucks together with the tether and brings them in contact as seen in Figure 3.

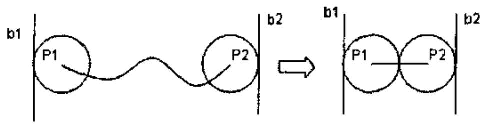

Figure 3. Reel-In Behavior.

The Mirror-Roll Behavior: Two Pucks that are in contact will rotate in opposite direction with equal motions. The effect of this behavior will allow the ends of the beams to dock and connect as seen in Figure 4.

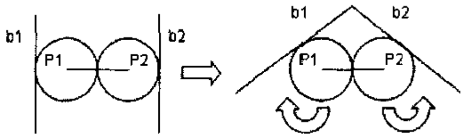

Figure 4. Mirror-Roll Behavior.

The Guide-In Behavior: To complete a single triangle truss unit, the Pucks must close the structure *from the outside*. Shown in Figure 5, this behavior assumes that a chain of three beams is already formed (b1-b2-b3). The two pucks P1 and P2 are attached to b1 and b3 from the same side and form the first configuration as shown. The Pucks will then rotate in opposite directions, and the effect will cause the tip of b1 and b3 to touch and connect.

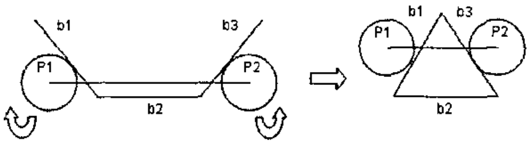

Figure 5. Guide-In Behavior.

With the four primitive behaviors defined above, we can achieve our task of assembling a triangle with three homogeneous free-floating beams. The steps in Figure 2 are explained as follows.

In step 1, the two FIMER Pucks perform a Go-Get to dock with two separated beams. In step 2, Reel-In the two beams together. In step 3, the two touching Pucks perform a Mirror-Roll causing the two beams to connect and form a 2-beam chain. In step 4-6, one Puck flies away to dock with the third beam and Reel-In to bring that beam close to the chain. The two touching Pucks then use Mirror-Roll to allow the two beams to connect. A 3-beam chain is thus formed. In step 8, the Puck connected to the middle is flying away to connect to the end beam and prepare a Guide-in behavior. Step 9 and 10 perform a Guide-In and a triangle is formed.

Although the above self-assembly process demonstrates the basic construction procedure, rarely will a single triangular truss be useful by itself. It is more likely that Pucks will continue to add onto the structure to create a more complex system. Figure 6 illustrates two additional processes to form larger and more complex structures.

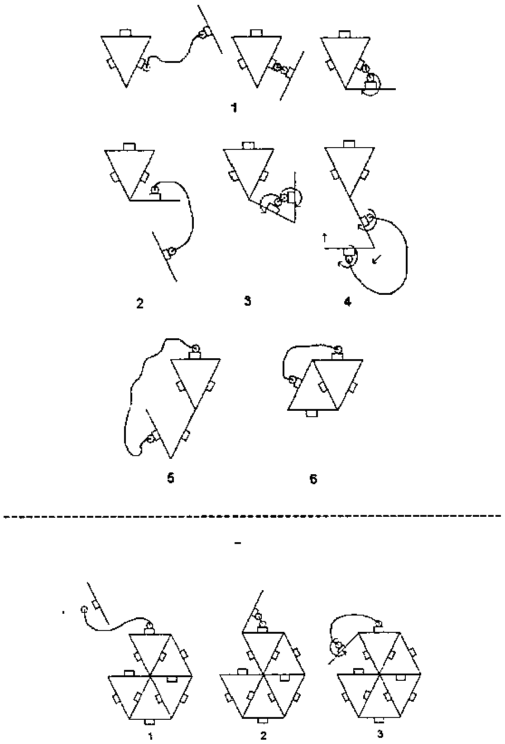

Figure 6. Augmenting an Existing Structure

III. EXPERIMENTAL SYSTEM

A. *Overall System*

We call our experimental system, SOLAR. Figure 7 shows the entire environment. When activated, air is pumped through the surface of a commercial air hockey table. This creates a bed of air on which objects can float effortlessly, effectively simulating a frictionless environment. The positions of the floating components and robots are sensed by a vision system that captures images from a camera directly above the table. Actuator commands generated for each FIMER Puck are broadcasted using a wireless transmitter

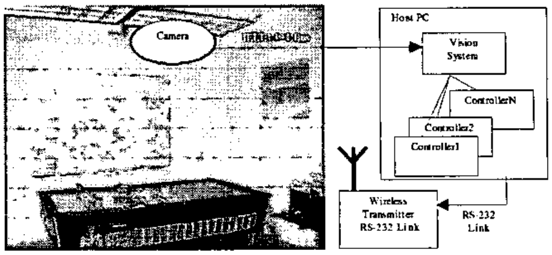

Figure 7. SOLAR Experimental Environment.

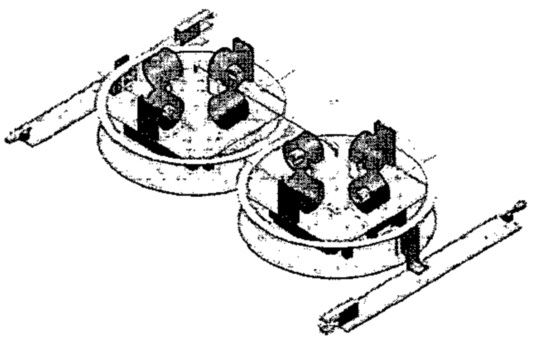

Figure 8. Two FIMER Pucks and Attached Beams.

A schematic is shown in Figure 8 of a double Puck FIMER connected by a tether and attached beams. Each Puck has an onboard microcontroller that controls 4 bi-directional fans and the tether. The fans are arranged in orthogonal directions to produce any desired thrust for translation and rotation. Each Puck has a wireless communication interface that can receive commands from the host PC.

B. *Mechanical Design*

A Puck must be able to "fly" on the air hockey table, so the contact surface at the bottom must be flat enough to provide an air cushion that eliminates friction. This surface must also have enough stiffness to prevent it from warping under the weight of all the components. Thus, a sheet of glass was selected for the bottom. The dimensions of the Puck are defined based on the weight and size of the components and the floating capacity of the bottom plate. The components are distributed symmetrically to have the center of mass as close as possible to the center of volume. The cylindrical shape of the Pucks (0.3m in diameter and 0.1m high) enables them to roll against each other while touching. The total weight is about 1.7kg.

A special tether mechanism has been designed so that a Puck will reel in the tether only when there is no tension and brake otherwise. This feature is for effective and efficient manipulation of objects in the environment [7].

The connectors used to dock among Pucks and components are described in [10].

C. *Control*

In dynamic environments, closed-loop control is essential to effectively plan, execute and monitor the self-assembly process. The control system must be able to sense objects of interest and alter the environment with the aid of actuators. We currently use a vision system for sensing the state of the system. Fiducials are used to mark the FIMER Pucks as well as the beams. Each fiducial consists of a large colored circle and a small circle composed of another color embedded in it. The centroids of each pair of circles are used to determine the position and orientation of that object.

Our vision resolution is 1.875 mm per pixel, which is more than enough accuracy for our purposes. Based on the sensed information and the history of movements, the control system generates the appropriate actuator commands for each Puck and broadcasts them through wireless communication.

The control problem presented by the approximated frictionless and weightless environment differs in comparison to most mobile robot control systems in that the system is not statically stable. There is noise and uncertainty everywhere. The table surface is not 100% even, the airflow is not uniform, and the fan thrusts may fluctuate. This noise is so prominent that an uncontrolled Puck will move randomly on the table. The controller must overcome all these obstacles to accomplish the task.

We use a simple proportional-derivative (PD) feedback controller to independently control our three degrees of freedom: two translations and one rotation. There are three equations:

$$F_x = -(K_D \dot{x} + K_P (x - x_d))$$
$$F_y = -(K_D \dot{y} + K_P (y - y_d))$$
$$F_\theta = -(G_D \dot{\theta} + G_P (\theta - \theta_d))$$

where K's are the translational gains and G's are the rotational gains.

Our PD controller is designed to maintain a desired orientation and position, but it receives data in the absolute coordinates provided by the camera. Whereas, the chassis of the Puck is rotating at varying rates and the fans are changing their direction of thrust. Therefore, we must transform absolute coordinates to local Puck coordinates in real-time in order to apply appropriate force values to each of the four fans.

Due to the nature of this environment, we discovered that one set of proportional and derivative gains is very effective in controlling the movement of the Puck, while a different set of gains is good for maintaining a stable position and orientation. In order to control the Puck and accomplish tasks, we have to dynamically switch between sets of gains based on the current task and situation. This leads to a more stable system and is necessary to achieve the required precision for assembly actions.

Since our robots are conducting complex tasks, we need a way to control the sequence of actions that provides input to the control system. We use simple state machines that sequence the behavior of FIMERs in pre-programmed plans. We transition on a state when a stage of the task has been completed and reset to the beginning if a failure has occurred.

IV. EXPERIMENTS

We have successfully implemented three primitive behaviors which, when composed together properly, will complete steps 1 through 7 of the 10 steps in our triangle assembly process.

A. *Go-Get Behavior*

We have successfully implemented Puck docking with a beam. Using a PD controller, we were able to set the correct gains and slowly advance the desired position towards the beam connector to make a slow and gradual approach. The connector tolerance was high enough to allow connection under most circumstances. However, control of the Puck is not good enough to guarantee hitting the target correctly 100% of the time. The system is programmed to try repeatedly until success, which usually occurred within 2 to 3 attempts. The drawback is that the beam needs to be rigid and not floating around on the table.

B. *Reel-In Behavior*

Once each Puck is docked with a beam, the tether between them needs to be reeled in and the Pucks pulled together to prepare for the Mirror-Roll assembly step. There are three requirements for a successful Reel-In operation. 1) No damage should occur either in the docked components, the Puck chassis, or the tether mechanism. 2) The system should remain stable during the process. The Pucks should not rotate out of control and crash into the walls of the table. 3) The operation must end with the Pucks in the correct position for a successful Mirror-Roll.

The tether mechanism uses a simple algorithm to guard against damage and prevent sudden jerks. When commanded, the motor begins to reel in the line while the tension is below a threshold. When the tension goes above the threshold, the motor stops and holds the line taut until the tension goes down again, upon which it restarts the motor. When the line can't be reeled any further, this prevents the motor from damaging itself. It also prevents the motors from causing sudden changes in velocity between the two Pucks.

Making the two Pucks stable during this process is difficult because they become coupled by their interactions through the tether. From experiments, we found that turning off the fans isn't really an option because this causes instability and crashing into the table walls. We also found that simultaneous complete position and orientation control for both Pucks also caused instability.

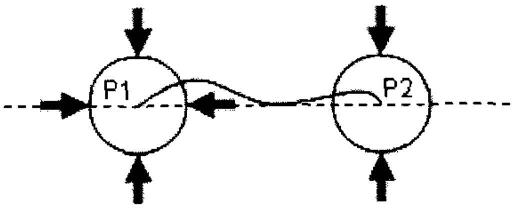

Figure 9. Reel-In Force Control Strategy.

Our solution was to do complete control for one Puck and do partial control for the other as seen in Figure 9. We assume that the two Pucks are along a fixed axis on which they need to stay aligned. However, Puck 1 controls its horizontal position while Puck 2 does not. Orientation control for both Pucks is maintained. This leads to a reasonably stable system.

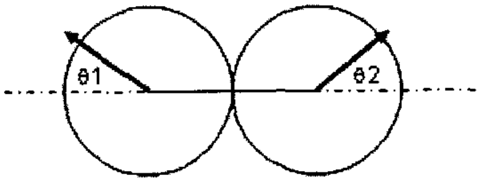

Figure 10. Mirror-Roll Initial Condition.

Finally, the Pucks need to come in contact at the correct initial position for the Mirror-Roll to succeed. This is critical because when the Pucks touch and the tether tightens, the Pucks are in static friction, and they act together like a pair of gears. This is a major advantage of the FIMER robot because it greatly simplifies the control of docking between two beams. The relationship between the two Pucks for the initial condition is illustrated in Figure 10. The arrows represent the facing orientation of the Pucks, and the axis is collinear to the Pucks' center of mass.

To achieve the correct initial condition, we must satisfy the following equation:

$$|\theta_2 - \theta_1| \le e$$

where e was empirically found to be about 8 degrees. The system must achieve this condition for the Mirror-Roll to succeed. We can detect the error using the vision system, and if it exceeds this tolerance, we can restart by releasing the tether using an SMA actuator and backing up the Pucks for another approach. We then turn the SMA off and begin reeling the tether again.

C. *Mirror-Roll Behavior*

When we have achieved the correct initial position specified by Figure 10, doing the Mirror-Roll and assembling the two beams is relatively simple. By being in this position, the trajectory of the beam connectors is guaranteed to intersect. We gradually increment the desired orientation of both Pucks at the same rate causing the Pucks to roll upon each other and mate the ends of the two beams. So long as the initial position is achieved with the specified tolerance, the operation is very reliable. During this process, the tether keeps two Pucks in contact without any slip so that the trajectories of the beam connectors will be guaranteed to intersect. The connection between the beam and the Puck must be secure and tight so that the bean and the Puck are moving together.

We have successfully combined Reel-In and Mirror-Roll into a single operation as seen in Figure 11. Videos of these operations are at www.isi.edu/robots/movies under the section labeled SOLAR.

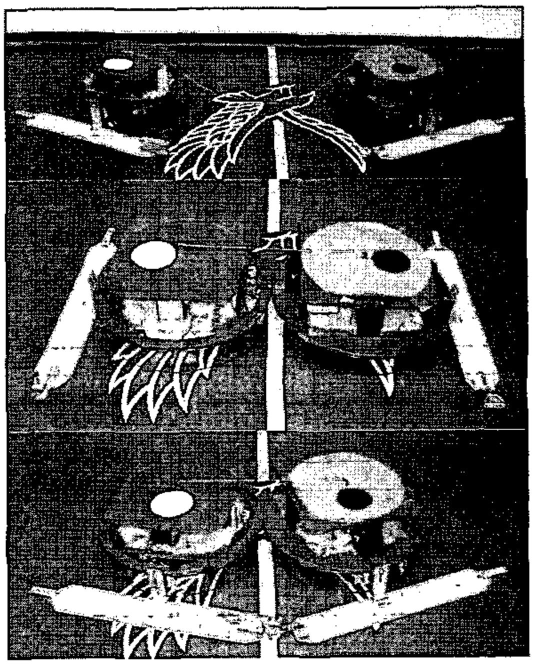

Figure 11. Reel-In & Mirror-Roll Assembly Steps

V. Discussion of Results

The constraints of our current design and test bed have set some fundamental limitations on how much we can control the Pucks. The emphasis of most of our control work has been on guaranteeing stability, reducing the degrees of freedom, and minimizing uncertainty. Though our system doesn't guarantee the outcome of an action, it can achieve an outcome with high probability with just a few repeated attempts.

We also exploit the geometry of the system to reduce the burden of our control. By turning the pair of Pucks into a set of gears, we can make geometric proofs of the outcome of rotation within a margin of error. By subsequently increasing the mechanical tolerance of our connectors, we mitigate this error.

The fact that our air table has boundaries to collide with has forced us to make tactical decisions that we would not take in an actual space environment. We may have put too much emphasis on maintaining a fixed position on the table where we could have introduced more subtle control if our workspace was much larger. The walls also make it very difficult to implement the entire assembly process in Figure 2 in one consecutive sequence. Doing so may require some creative engineering.

VI. Conclusion & Future Work

We have introduced an experimental environment for in-space robotic-assembly. We have demonstrated some successful assembly experiments that assemble two beams together that can be used to make a triangle. We believe this approach is capable of assembling large-scale structures in space.

Future work will focus on completing the triangle task, researching the most appropriate assembly tactics, refining beam-Puck and beam-beam connectors, expanding to larger-scale structures beyond simple triangles, and developing multi-FIMER distributed assembly algorithms.

Acknowledgments

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