# Self-Assembly in Space via Self-Reconfigurable Robots

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*Abstract* — **Self-assembly systems in space are arguably within the reach of today's technology based on the research and development of self-reconfigurable robots on earth. This paper presents an approach to self-assembly in space by developing (1) a novel design for intelligent and reconfigurable components; (2) the free-flying "intelligent fiber/rope" "match-maker" robots with self-reconfigurable and self-adjustable tethering for autonomous docking; and (3) a totally distributed control method for planning, executing, and monitoring the assembly process. These approaches are partially evaluated by a set of experimental and simulation results to simulate the dynamics and control of free-flying objects in zero-gravity environment.**

## 1. INTRODUCTION

Future structures in space are likely to be big and complex. For example, a proposed Space Solar Power System will have structures that are 10km on each side. Previous methods for assembling such structures in space are centered on astronauts, which is feasible for short and quick tasks. However, such a method is too expensive and risky when an assembly job is complex and requires many hours of space walking. For example, a typical solar power system will have at least 2,500 components, then the entire structure would cost at least 10,000 space walking hours and more than $10 billion. Thus, self-assembly in space is a necessary process for building cost-effective space structures. One can imagine that all components are intelligent and free flying. Once delivered in space, they will automatically search, navigate, find, and dock to each other to form the designed structures. Their individual activities are flexible, adaptive, robust, and fault-tolerant to ensure the success of self-assembly. The free flying ability is enabled either by onboard engines or by some innovative mechanisms for remote pulling and pushing. Human interventions will be built-in as an option for emergency or special tasks.

We believe that such a self-assembly system is within the reach of today's technology based on the research and development of self-reconfigurable robotics on earth. In particular, this paper presents (1) a novel design for intelligent and reconfigurable space components; (2) the free-flying "match-maker" robots with self-reconfigurable and self-adjustable tethering for autonomous docking; (3) a totally distributed control method for planning, executing, and monitoring the assembly process.

## 2. OVERVIEW OF SELF-ASSEMBLY IN SPACE

Our core approach to space self-assembly is to make each structure component intelligent and reconfigurable, and accomplish autonomous docking by the free-flying self-reconfigurable match-maker robots. To illustrate the main ideas, consider the scenario in Figure 1 where a set of reconfigurable components is assembled by the free-flying "intelligent fiber/rope" "match-maker" (FIMER) robots. In this figure, the objects with multiple disks are components to be assembled. Some are single components (which have four disks each) and others are already assembled in multi-component structures (more than four disks). All components have GPS and can communicate with others wirelessly. Components are connected to each others using a set of connectors (in this example, the two connectors are located at ends of the main shaft). All connectors are canonically designed so that any two connectors can dock or de-dock at will. The connectors also facilitate auxiliary connections for fluid/gas pipes and electric connections so that the assembled structure can function as a single unit.

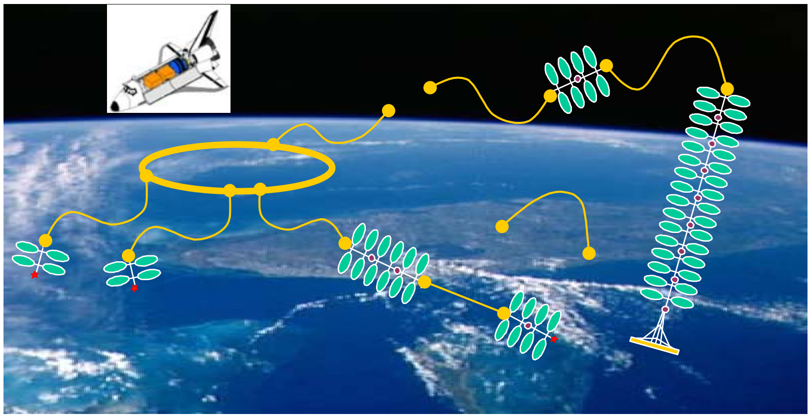

Figure 1: Self-Assembly Using Free-Flying Intelligent Rope Robots.

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. Each head can fly autonomously and communicate and dock/de-dock with any component or other FIMER robots. It has onboard power, engine (for flying), motor (for reeling), navigation sensors (GPS), a wireless communicator, a flexible robot arm (for simple grasp and manipulation), and a reconfigurable connector. 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 line. When the two heads are attached to two different components/structures, a FIMER robot can pull the two parties together and make them dock each other. A FIMER robot can also hold components to a "storage structure" (shown as the large ring in Figure 1) to prevent them flying away from the construction site. Ideally, the FIMER robots are solar-powered and use flying engines that need no refueling (such as Ion motors). Compared to complete free-flying approaches, the control and navigation of the FIMER robots are much simpler because of the tether and the ability to attach to other structures. Compared to a complete tethered system, the FIMER robots are much more flexible because their attachments are dynamic and reconfigurable.

The self-assembly process is orchestrated by a totally distributed control mechanism called the Digital Hormone Model [1-3] developed in the CONRO reconfigurable robots. Components will negotiate among themselves to decide which two components/connectors must be dock together next. The to-be-docked components will broadcast the dock-calling signals and call a FIMER to help. A FIMER will respond to such callings by flying and connecting its heads to the calling connectors. (Multiple FIMERs will join their lengths if the two components are too far away for a single FIMER.) Once the heads of a FIMER are attached to the components, the FIMER will pull the components together by reeling in the tethered line. When two components (connectors) are close in distance, the FIMER will use its robot arms to grasp the connectors, guide the docking process, and fasten the connections. After the connection is made, the FIMER will fly away for other tasks. Human interventions can be injected any time by wireless communication with the FIMERs. All FIMERs can refuel their engine at the storage station or the space shuttle when needed.

## 3. SELF-RECONFIGURABLE ROBOTS

Self-reconfigurable robots will sever as an important inspiration source for the space self-assembly techniques. These robots are made of autonomous modules that can connect to each other to form different configurations. The connections between modules are dynamic and can be changed autonomously by the modules themselves. Because of this dynamism, communication among modules can be adaptive to topological changes in the network. Furthermore, since each module is autonomous and self-reconfigurable (has its own power, controller, communicator, sensors, actuators, and connectors), modules in a self-reconfigurable robot collaborate and synchronize their actions in order to accomplish desired global effects. All these features are essential in a self-assembly system. We can think of a reconfigurable module as a structure component, and a configurable robot as the final self-assembled system.

Figure 2: CONRO module and robots in configurations of snake, insects, and rolling track.

To illustrate the ideas, we use the CONRO self-reconfigurable robot [1-8] as an illustration for typical self-reconfigurable modules and control concepts and algorithms. Shown in Figure 2, CONRO is a robot made of a set of small-sized modules that can autonomously and physically connect to each other to form different configurations such as chains, trees, (i.e., legged-bodies), or loops. For example, a CONRO robot can become a "crab" and climb over rubble and then smoothly morph to a "snake" to slither down between the stones to locate a person or some artifact. They can become a ball to roll down a hill, or transform a leg into a gripper to perform a grasping operation. The control of these modules are totally distributed and based on a biologically inspired approach called Digital Hormone Models [1-3] and the role-based control [7, 8] so that modules can self-discover their local topology in deciding their actions, and can self-repair their structures for unexpected situations, and can physically change their topological structures while the entire robot is still in operation. No permanent "brain" modules exist in the system but any module can dynamically become a leader as its local topology is appropriate. Damage to single module will not paralyze the entire operation. For movies and other information about CONRO, please visit http://www.isi.edu/conro.

## 4. INTELLIGENT RECONFIGURABLE COMPONENTS

To apply the concepts of self-reconfigurable robots to self-assembly in space, we envision to make every component an Intelligent and Reconfigurable Component (IRC) by including the following capabilities: (1) a set of canonical connectors to dock with other components and FIMER robots; (2) a position and orientation sensory system; (3) a wireless communication unit; and (4) an onboard controller for topology discovery, action planning, communication with FIMERs and other IRCs, and monitoring the progress of assembly. An IRC will be self-sufficient for power in the assembly process, and it is free float in the space.

Each IRC will have a set of reconfigurable connectors that can be used to dock with other IRCs and FIMERs. Such connectors should have a compliant mechanism for easy docking and a tightening mechanism for stress endurance and precision. Each connector must also have sensors to detect the status of the connector (docked or not) and to provide precision guidance in the docking process. Connectors should be able to report their statues to the onboard controller and receive commands from the controller. The connectors must be *hermaphroditic* (genderless) so that any two connectors can dock together. To insure the correct orientation in self-assembly, the connectors must be designed to allow only one possible alignment. Since space has near-zero gravity, a pulling method for docking will be much more predictable than a pushing method because any uncontrolled and non-tethered pushing force would cause the docking parties to move in an unpredictable manner.

To illustrate the concept of connectors, Figure 3 illustrates a type of connector that is designed based on the existing connectors used in the CONRO robots [9, 10]. The docking process of this connector is based on pulling. It has two pins, two holes, and two “whiskers” that come out of the center of the pin. These whiskers are made of thin and lightweight metal. The tip of the whisker has a hook. Since it is thin and lightweight, a whisker can extend and gently enter a docking hole and hook at the end of the hole without disturbing the relative positions of two docking components. Once a whisker is hooked, it will retract and pull the other connector closer, and the two connectors will mutually dock. When the whiskers are pulled all the way to the end, the two pins will be securely locked by the receiving latches (shown as brown elements in Figure 3). This connector design is hermaphroditic and will greatly reduce the disturbance to the two docking components, and can make the connection strong and secure. The connectors can be released by opening the latches for the pins and the whiskers [9, 10].

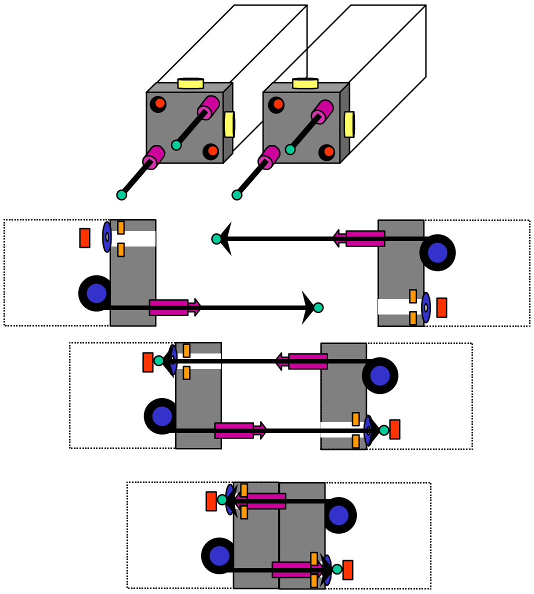

Figure 3: The genderless pulling connectors

The connectors will use Infrared to provide guiding signals for alignment in the docking process just as used in the CONRO connectors [6, 11-23]. Each side of the connector will have two emitters and two receivers and they are arranged in such a way that when two sides are aligned they will have the maximal signal receptions. The unique feature that is not discussed in detail in the literature is the whole area of accommodating for tolerances. Also not discussed as a part of the docking problem, apart from the work of Shen and Will [6], is the control of mutual relative motion of both docking parties.

To support navigation and autonomous docking among IRCs during self-assembly, each IRC will use GPS to detect its current position. The orientation can be either detected by an onboard inertial navigation system or computed from two GPS that are installed away from each other on the IRC [24]. Based on the position and orientation, each IRC can compute the position and orientation for each of its connectors. Such information is necessary when two IRCs must dock two particular connectors together with the help of FIMER robots.

The communication between IRCs can be divided into two cases: when they are connected, and when they are separated in space. For the first case, they use the IR sensors and emitters similar to those used in the CONRO module [6]. Such a communication device is associated with each connector, so that IRCs in an assembled structure can discover the topology of the structure. Wireless radio will be used for remote communication, which will facilitate the search of docking partners, human instructions, and negotiation of assembly actions.

Each IRC will have an onboard computer that will control the information gathering, processing, and communication. One of the most important tasks for the controller is to discover the status of the current assembly process (such as the current topology) and negotiate with other IRCs to select the proper actions for the assembly. To discover the local topology, each IRC will probe every one of its connectors (use the sensors at the connector) to see if there is any neighbor IRC on that connector, and if so which connector of the neighbor it is connected to. This information is maintained in a local state variable. This variable will be update to reflect not only the status of whether a connector has a neighbor, but also to which connector the neighbor is connected. The later information is critical for determining the local topology. All IRCs in the same structure will exchange such local topology, and together they can discover the current topology for the assembly, and decide the next actions to be performed.

## 5. THE FIMER ROBOTS

To the best of our knowledge, the concept of Free-Flying Intelligent Fiber/Rope Match-Maker (FIMER) Robots is a novel one. Shown in Figure 4, each FIMER has two heads linked by a tether line that can be reeled in or out by the heads. At the tip of the head is a reconfigurable connector that can be docked to and de-docked from any other connector in the entire assembly system. On the side of a head, two thrusters are located at the opposite directions, and each of which can rotate $360^{o}$. These thrusters can be implemented by either Ion motors [25] or inkjet custom miniature thrusters based on inkjet printer technology. Each head also has a flexible robotic arm with a grasper. These arms are used to guide the autonomous docking between IRCs. We propose to use VECTRAN fiber as the tether line (a 3mm thin fiber can endure 1,800lb of weight) just as the tethered gripper system [26]. Each FIMER head has a brake system when reeling in or out the line, so that they can adjust the length of the tether line between them for controlling purposes. Each FIMER is a self-sufficient and autonomous system with its own power, fuel (if jets are used), thrusters, electrical motors, controller, GPS, wireless communicator, and a simple robot gripper.

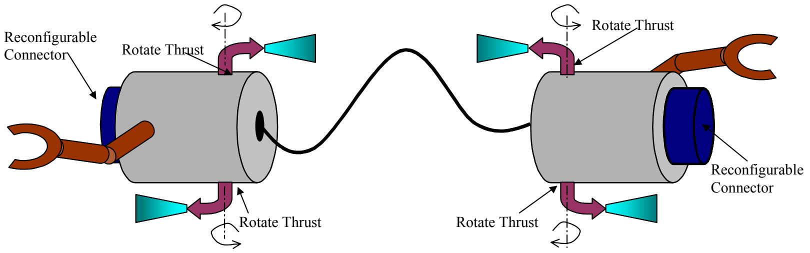

Figure 4: A FIMER robot with two free-flying heads

The property of mutual-tethering and self-reconfiguring of FIMER can greatly simplify the control of the free-flying robot in micro-gravity environment while preserving the flexibility for self-assembly. In such an environment, parts need to be (1) brought to the assembly site; (2) maneuvered in space to the assembly point; (3) fastened when they are connected.

One of the main tasks for the FIMER robots is to establish docking between IRCs. This task includes the following steps: (1) finding the two IRCs and their connectors to be docked; (2) bringing the two IRCs together so that their connectors are near and aligned; (3) fastening the connection by inserting and locking the docking mechanism; (4) establishing the auxiliary hose connections for gas/liquid/electrics.

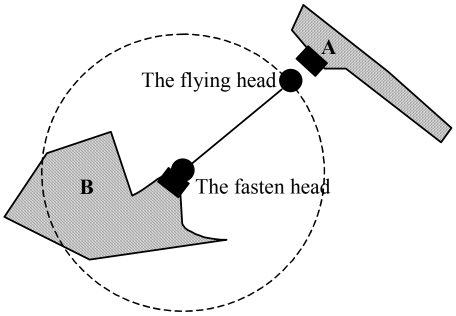

Figure 5: The control of tethered maneuver

When two IRCs are to be docked, they will broadcast a call for dock with the information about the two connectors' locations and orientations. A free FIMER robot that is closest to the two connectors will respond to the call by flying and connecting its two heads with the two connectors to be docked (these connectors are typically away from each other in a distance). To accomplish this task, Figure 5 shows the most basic movement of a FIMER robot: to fly and dock one head to a designated connector on structure A while the other head is fasten on a structure B. This task is simpler than flying a completely free object to join another completely free object because the tether line. To see this, notice that when the flying head is moving in space, the combination of forward thrust and tethering will constrain its movement on a surface of a sphere defined by the current length of the tethering line. To fly forward in a straight line from the tethered point, the flying head can reel out the line gradually while keeping forward thrusting. When the flying head is near the connector to be docked, the gripper can grasp the connector and fasten the connector on the head to the connector on the structure. If the connector to be docked is on the other side of the structure A, then the flying head must use its thruster to fly around the structure and dock itself there. If two structures are too far away for a single FIMER to reach, multiple FIMERs can join together to increase the length of tether line.

After the two heads are fastened on the two connectors, they will reel in the tether line and pull the two objects towards each other. The pulling should be slow and careful to avoid unnecessary acceleration. One algorithm is to *reel in the line only when there is no tension on the line* so that there will be no unwanted force applied to the moving structures. During the pulling process, the two heads can also use their thrusters to decelerate the movement of the structures if necessary, or rotate an object using the thrusters on the head so that the docking connector will be aligned in rotation when it is approaching to its docking partner. When the tether line is pulled all the way in, the grippers on either heads will grasp the connector on the other side, and detach their heads from the structure's connector (which should now be docked to each other) and use the grippers to guide the final stage of docking and fastening. For easy grasping, each connector will have a handler for the FIMER robots to hold.

In addition for docking, FIMER can also clamber around the interior of a structure if needed. To do so, the heads of a FIMER will alternatively fly to the next open connector while the other is fastened on another connector on the structure. The FIMER can wirelessly communicate with any IRC or other FIMER robots. Using the GPS location information received on radio, a FIMER robot can fly to a designated point. To avoid collision during navigation, each IRC will broadcast their location and a flying FIMER will use that knowledge to plan its flying course to avoid collisions.

The dynamics of mutually pulling objects in the micro-gravity environment is an interesting research topic and it depends on the amount of pulling force, the mass of the objects, the relative positions of the pulling points with respect to the objects' center of mass, and the time when the pulling is applied. Typically, when a pulling force is applied, the object will spin and move at the same time. The FIMER robot will use a simple algorithm for de-spinning objects in space, that is, *to reel in the line whenever there is no tension*. To see how this may work, consider again the situation in Figure 5. Suppose that the line is reeled in by a small force for a short time, the object A will start spinning counterclockwise while it is moving. As the object A spins, the line will lose its tension (because the pulling point becomes closer to the object B) and it will be reeled in. At some moment later, the counterclockwise spinning of object A will be stopped by the line and a clockwise spinning will start. The oscillation of spinning will continue but momentum will reduce every time the direction of spinning is changed. Eventually, the oscillation will converge to zero and the pulling force will be aligned with the object's center of mass. This is similar to the situation when a coin is dropped on a table and it's flip-flop actions will oscillate many times before it settles down. However, we do not have a theoretical proof for this at this time.

One problem for the above argument for de-spinning is that some spinning may be so large that the spinning object will hit the tethered line or other objects. To prevent this from happening, one option is to use two strings for stabilizing spinning objects in 2D environments (as two floating objects on water mutually pulling each other), and three strings for 3D environments. The control of each pulling string is the same: reel in whenever there is no tension on the line. The objective is to use as few lines as possible, as long as the spinning oscillation converges to zero. In the experiments we conducted on the surface of water, one string is sufficient for this purpose because the small friction between water and the floating object. Another open problem for mutually pulling dynamics is how to prevent the tether lines from tangling among themselves or snagging on some objects unexpectedly. To prevent tangling, all FIMER will reel in their lines when not active.

## 6. DISTRIBUTED CONTROL FOR SELF-ASSEMBLY

To effectively plan, execute, and monitor the self-assembly process, we use a distributed control method where the sequence of self-assembly is embedded in the IRC themselves. This is inspired by the hormone-inspired distributed control mechanism developed in the CONRO reconfigurable robots [2, 3, 5]. We view an assembly as a network of components joined with connectors, and each component in the assembly as an active cell that can dynamically discover its local topological changes and adjust its communication and control strategy accordingly. We assume that every connector in the assembly has a unique identifier. A connector can be activated to participant in a docking by wireless communication from other IRCs or from human operators. The activated connectors will broadcast dock-calling signals to call FIMER robots to assist the docking. After the docking is accomplished, the controllers of the docked IRCs (recall that every connector belongs to an IRC and every IRC has a controller) will retrieve from their memory the next two connectors to be docked and send out signals to activate them. This procedure continues until all the connectors in the assembly are properly docked. The sequence of connector identifiers is so designed that the required docking is possible at the time when the connectors are activated. To make the process more flexible, the calling signals may be a type of component (instead of individual ids) so that any component matches with the called type can be activated. This solution can also support human intervention in the assembly. A human operator can wirelessly deactivate the activated connectors, activate other connectors, and change the course of assembly.

To illustrate the above ideas, Figure 5 illustrates a simple example to show how a tetrahedron is assembled in steps from a set of six reconfigurable beams. The active dock-calling radio signals are shown as stars in Figure 5. In this example, we assume that the connectors on the beams can rotate and they are located at the end of the beams.

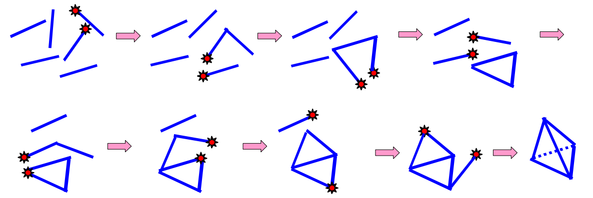

Figure 5: A Sequence of Self-Assembly

To increase the efficiency of the assembly, we could also allow multiple connections to be made simultaneously. This is possible if connections are not interdependent and can be made separately at the same time. Special attention must be paid to those connections that must be made in sequence. Another possible relaxation is that we could allow connections to be disconnected under control, similar to those in a self-reconfigurable robot. This will provide the metamorphic ability to allow an existing space structure to change into a different structure. Such a reconfigurable ability may be very important if self-maintenance or self-repair in space are needed in the future.

The self-assembly process must also have the ability to self-monitor its own progress because there may be no continuous observation from humans. The assembly process must detect errors and abnormalities and report to humans for instructions. For example, if an IRC has broadcast the connector identifiers for the next connection but receives no response after a long period of time, then it must report this abnormality or else the assembly process will not make any progress. More elaborated monitoring ability must involve self-discovering the topology of structures. In self-assembly process, every time a new connection is made and the resultant structure must check if it matches to the expected topology.

## 7. SIMULATION RESULTS

At the time this paper is written, we have conducted some initial experiments in simulation to validate the concepts in this paper. In particular, we have implemented the FIMER robots as a set of "flying ropes" in a zero-gravity environment in a commercial simulation environment called the 3D Working Model. We are implementing the algorithm of "pulling when no tension" and observed that objects can indeed be pulled together without spinning forever. We have also conducted the similar experiments on the surface of water. To simulate the reel-in algorithm in hardware, we have used a fishing rod with reel-in capability and modified the tension sensors. This device is used to pulling a floating heavy object through normal fishing line in a distance. We observe that the initial pulling force will cause the object to spin at the beginning, but whenever the fishing line is reeled in when there is no tension (we simulated this by hand and the tension is detected by human eyes on the curve of the fishing line), the spinning is reduced. Eventually, the object is pulling in smoothly without any spinning. We have made movies of this phenomenon, and the interested readers can find the video on http://www.isi.edu/robots. We realize that this experiment is not entirely gravity-free and frication-free, and more elaborated experiments will be done on a large air-hockey table, possibly in the facility at the NASA Johnson Space center. Supported by NASA and NSF, we are in the process of building the IRC and FIMER robots in small scale environment, and more experimental results will be reported in the near future.

## 8. CONCLUSION

This paper argues that self-assembly in space is within the reach of today's technology developed in the self-reconfigurable robots, and presents a set of novel solutions for such assembly process, including the intelligent and reconfigurable components with connectors and controllers, the FIMER robots for autonomous docking, and the embedded and distributed control method for planning, executing, and monitoring the assembly process. Although these concepts are not yet fully implemented, the initial experimental results (in simulation, on water surface, and docking between physical modules on the ground) have shown the potential of the approach.

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