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A Semi-Autonomous Replicating Robotic System

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Abstract

The concept of self-replicating machines was introduced more than fifty years ago by John von Neumann. However, a fully autonomous self-replicating robot has yet to be implemented. This paper discusses our ongoing research on self-replicating robots. Here we describe a semi-autonomous prototype that can demonstrate replication under human supervision. This work builds on our previous results in remote-controlled robotic replication with the added feature that many subtasks in the replication process are now autonomously performed by the robot. We believe this to be an important step in the realization of fully autonomous self-replicating robots.

1. Introduction

In this paper, we develop a set of underlying principles for self-replicating robotic systems, and demonstrate a physical prototype capable of replication under human supervision. Our prototype is constructed from modified LEGO Mindstorm kits in which the electrical connections are enhanced. We also discuss the motivation for studying self-replicating systems and review earlier related works. Finally, results of experiments with our prototype system are discussed.

1.1 Motivation

Imagine a factory that requires neither people nor the monstrous machinery typically associated with a factory - a factory that autonomously replicates itself for multiple generations. Over the years, outer space has been mentioned as one potential application for such self-replicating robotic factories [1-3]. However, enormous technical barriers must be overcome before these systems can be realized. The purpose of the current work is to take one small step toward realizing this goal.

In contrast to self-reconfiguration [4-8], self-replication utilizes an original unit to actively assemble an exact copy of itself from passive components. The copies themselves then self-replicate and may or may not assist the original unit in its self-replication process. In either case, the number of assembled units will exponentially increase, reducing the required time to finish the original unit's task.

1.2 Previous Efforts in Mechanical Self-Replicating System

In 1920, Czech playwright Karel Capek first coined the term *robot* with his visionary play, *RUR (Rossum's Universal Robots)*, which tells the story of robots who turn on their human creators. In that play, the issue of robotic replication was alluded to in passing. Von Neumann [9] was the first to seriously study the idea of self-replicating machines from a theoretical perspective. Von Neumann introduced the theory of automata and established a quantitative definition of self-replication. His early results on self-replicating machines have become useful in several diverse research areas such as: cellular automata, nano-technology, macromolecular chemistry, and computer programming (for more details see [10].)

One of the most well-known demonstrations of self-replicating mechanical systems was performed by Penrose in the late 1950's [11]. It consisted of passive elements that self-assembled only under external agitation. In other words, even though the system was able to self-replicate mechanically, the system alone lacked the ability to self-assemble from passive components into the desired configuration due to the lack of internal actuation. In a sense, Penrose's design was more of a self-assembling structure rather than a self-replicating machine, and the modern work of Whitesides (e.g., [12]) is very much in the spirit of this work.

More than 20 years after Penrose, NASA established a series of studies on the topic of "Advanced Automation for Space Missions" [1]. One such study examined the possibility of building a self-replicating factory on the moon, utilizing solar energy and materials found on the moon. A number of papers were also published at that time concerning the various applications of self-replicating machines in space [13-16]. Although none of the ideas came to fruition, such a large number of possible applications both on Earth and in space continues to fuel interest in the development of self-replicating robots. Recently, research on robots that are able to design other machines with little help from humans has also been performed (see [17] and references therein). This relies on the use of rapid prototyping technologies.

2. Principles for Self-Replicating Robots

We divide self-replicating robots into two primary categories: Directly Replicating and Indirectly Replicating (Figure 1). A "directly-replicating" robot is capable of producing an exact replica of itself in one generation. A robot that produces one or more intermediate robots that are in turn capable of producing replicas of the original is described as "indirectly replicating".

2.1 Directly-Replicating Robots

Directly-replicating robots are divided into four groups based on the characteristics of their self-replication processes: fixture-based, operating-subsystem-in-process, single-robot-without-fixture, and multi-robot-without-fixture.

2.1.1 Fixture-Based Group

Fixture-based groups depend on external passive fixtures for self-replication. These external fixtures may range from the simplest mechanisms, such as a hook, to highly intricate fixtures required for restraining delicate parts during assembly procedures. Regardless of the complexity of a fixture, they serve as crucial elements to complete the self-replication process, but are themselves not actuated.

2.1.2 Operating-Subsystem-in-Process Group

In this group, one or several subsystems of the replica can operate before the replica itself is fully assembled. As a result, these subsystems are able to assist the original self-replicating robot during the assembly of the replica. Hence, these functioning subsystems can aid in various ways such as aligning, manipulating, or transporting parts.

2.1.3 Single-Robot-Without-Fixture Group

This group utilizes only one robot to self-replicate. Thus, the robot depends solely on the available environment. Although this group would seem to be the best method of self-replication due to its independence, there is a drawback; the complexity and functionality of the robot tend to be low as is the number of subsystems in the replica for this group. This is due to the difficulty associated with positioning large numbers of subsystems with high precision without fixtures or multiple cooperating robots.

2.1.4 Multi-Robot-Without-Fixture Group

Each system in this group consists of a collection of robots working together to self-replicate without fixtures. A major advantage is faster self-replication since different stages can be completed in parallel. However, the robots must possess a greater awareness of their surroundings, especially with regard to the other robots, resulting in interference problems among the robots. In addition, multiple robots require multiple replicas that must be produced.

2.2 Indirectly-Replicating Robots

The core characteristic of the robots in this category is their inability to make copies of themselves without first producing systems with architectures different than themselves. These intermediates (which are constructed by the original robot) would then be able to produce replicas of the original robot, or assist the original robot in replicating. This group is divided into those robots that require intermediate robot(s) and those that are part of a self-replicating factory.

2.2.1 Intermediate Robot(s)

In this group, the original robot works alone or with other robots, with or without the use of passive fixtures, to fabricate an intermediate robot or robots. These intermediate robots possess the ability to fabricate, or assist in fabricating, replicas of the original robot that the original robot itself does not.

2.2.2 Self-Replicating Factory

In this case, the robot either works independently or in a group to construct a factory consisting of automated workcells that can then manufacture replicas of the original robot. The workcells in the factory differ from the intermediate robots and passive fixtures in the category above because they are fixed automation elements that can be fully actuated.

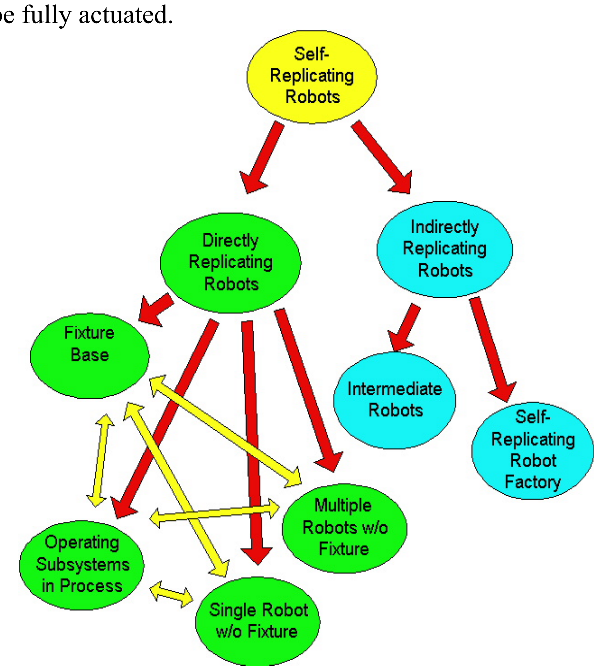

Figure 1: The Block diagram of the categorization of self-replicating robots.

Due to the countless ways that self-replication can be categorized in the groups above, more categories are likely to be developed as more research is conducted.

3. Design and Descriptions of a Semi-Autonomous Replicating System

Our semi-autonomous replicating system is an example of a robotic factory, as defined in the previous section. The system consists of an original robot (denoted as "robot1"), subsystems of three assembly stations (Station 1, 2, and 3), and a set of subsystems from which replicas of the original robot are assembled.

Robot1 and its replica each consists of five subsystems: a robot control system (RCX), chassis, left-track, right-track, and a motor/sensor unit. Figure 2 shows an exploded view of the robot (and the gripper). The RCX is the brain of the robot as it receives instructions from a separate remote and runs five different programs that can be written by the user. Not only does it control the robot, but it also provides electrical power. The motor/sensor unit comprised of two 9V Lego motors, is used to drive the tracks, and carries two light-sensors; these light-sensors are feedback sensors to track a painted line in the experiment area. With lines drawn between the three stations, a robot is able to move autonomously from station to station along the lines without any input (Figure 3), while being remotely controlled at each station. As a result, this system is aptly described as semi-autonomous.

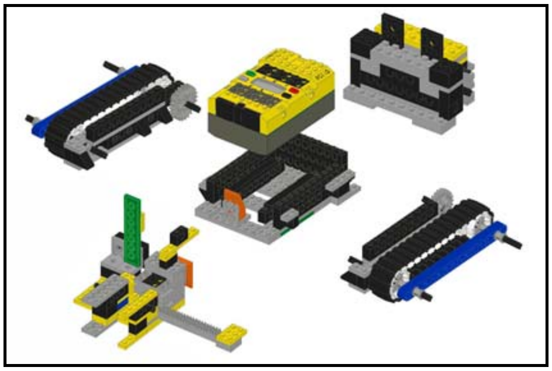

Figure 2: An exploded view of Robot1.

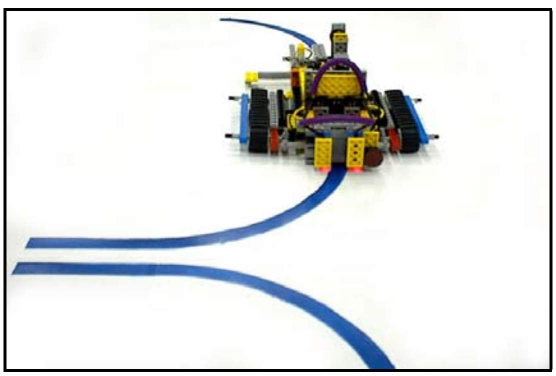

Figure 3: Robot1 autonomously tracking a painted line with the light sensors.

Station 1 (Figure 4) combines the RCX with the chassis. It consists of four subsystems: conveyor-belt/sensor unit, docking unit, electrical connection, and central controller unit (CCU). The conveyor-belt/sensor unit attaches to the docking unit and the CCU via the electrical connection, which provides the electrical power and control. Station 1 automatically activates when the chassis is aligned into the assembly position by robot1 (Figure 5). The feedback system powers the conveyor-belt to autonomously assemble the RCX to the chassis.

Station 2 (Figure 6) assembles the left and right tracks to the combined RCX-chassis unit. Station 2 is comprised of a left and right hook, CCU, electrical connection, stationary docking sensor, and a motorized pulley unit. Robot1 places the two tracks inside each hook and aligns them perpendicular to the pulley unit, driven by a single 9V Lego motor with a differential gear and two sets of reduction gear/belt systems. The motor rotates two gears, connected to the hooks by a rack and pinion system, in opposite directions on either side. In order to place the hook in contact with the pulley gears, robot1 requires a higher precision of alignment. Therefore, robot1 moves onto station 3 to retrieve a gripper for this operation, further described in the next section. After positioning the replica's subsystems into appropriate positions, station 2 is automatically activated by a light-sensor, located in the middle of the pulley unit (Figure 7). Both hooks are then driven to attach both tracks to the finished chassis unit. Robot1 proceeds to the docking area and triggers station 2 to release the finished replica.

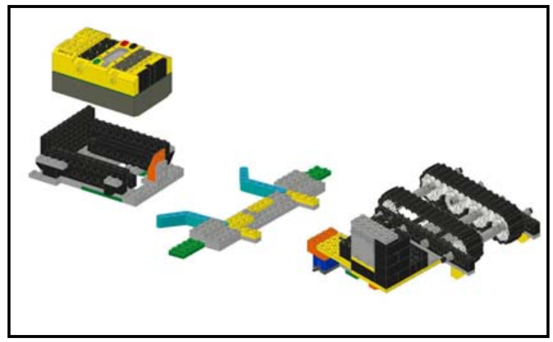

Figure 4: An exploded view of station 1 and the replica's subsystems.

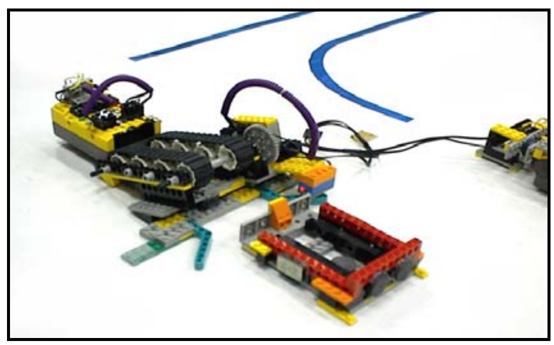

Figure 5: Activation of station 1 when the chassis triggers the station's light sensor.

Station 3 attaches a motorized gripper arm to robot1. The gripper is an example of interchangeable tools of the robot due to the ease of replacing the gripper with other types of tools. A motor is used to drive a rack and pinion system to open and close the jaws of the gripper. An electrical connection is made between the gripper and the RCX, allowing control of the gripper. Station 3 consists of a CCU, an electrical connection, a ramp and lift system used to displace the gripper up and down (Figure 8). Figure 9 shows the active fixture in operation.

In this experimental set-up, all three stations utilize the same CCU, a programmable Lego RCX 2.0 with modified electrical connections. Subsystems of all stations are built of exclusively Lego parts. A number of magnets are used to assist in alignments and electrical connections. Figure 10 illustrates the map of the experimental set up.

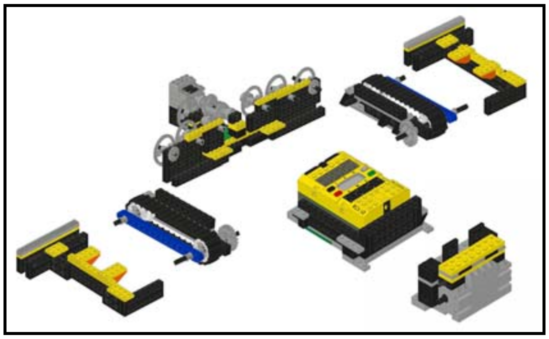

Figure 6: An exploded view of station 2 and the replica's subsystems.

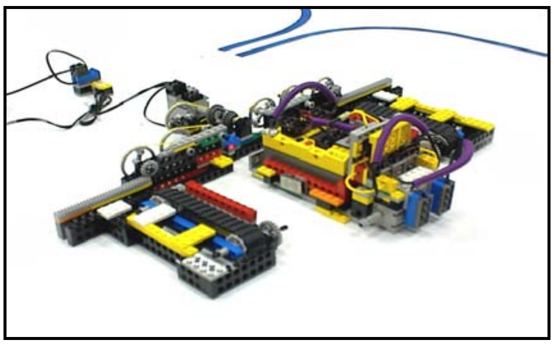

Figure 7: Activation of station 2 when the chassis triggers the station's light sensor.

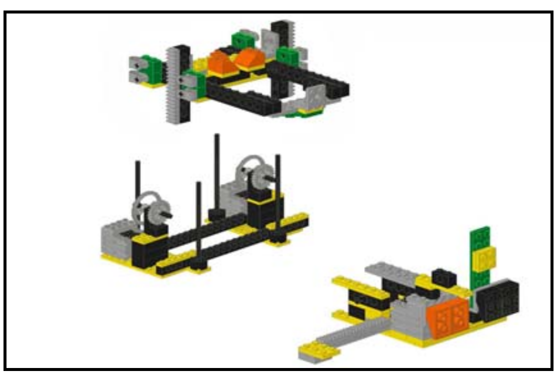

Figure 8: An exploded view of station 3 and the gripper unit.

4. Experiments and Results

The following is a step-by-step procedure for the "Semi-Autonomous Replication System": (see Figure 11 simultaneously)

Station 1 – Chassis Assembly

Fixture Components:	Replica Components:
1. Conveyor Belt/Sensor Unit	1. Robot Chassis
2. Dock	2. Robot Control System 2 (RCX2)
3. Central Control Unit (CCU)	

a. Wire Connections

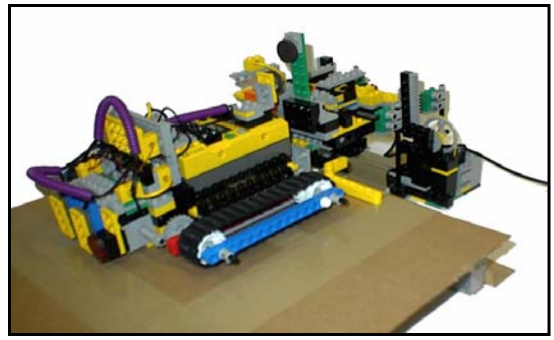

Figure 9: Station 3 with the ramp.

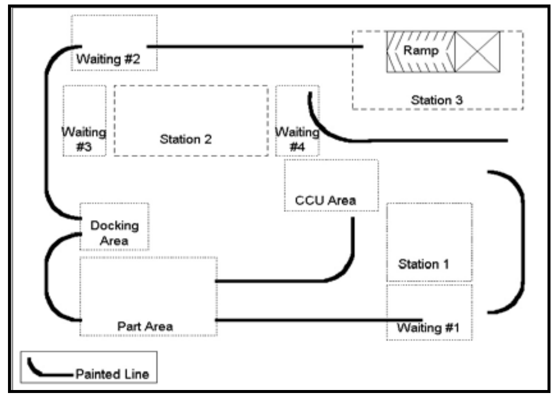

Figure 10: Experiment setup map.

Operational Procedure for Robot1:

1. Move chassis to waiting area #1 and then autonomously return to part area for next step.
2. Lock conveyor belt/sensor unit to the docking part of station 1.
3. Move CCU to the CCU area.
4. Connect wires from the belt/sensor unit to the CCU.
5. Move RCX2 to front of the belt until system activation.
6. Align chassis into position while the system is automatically activated by sensor detecting the chassis unit.
7. Push RCX2 onto the conveyor belt until it is placed on top of the chassis.
8. Move assembled chassis to station 2.

Station 2 – Motor and Track Assembly

Fixture Components:	Replica Components:
1. Left and Right Hooks	1. Left and Right Tracks
2. Motorized Pulley System	2. Assembled Chassis(from St 1)
3. Docking Sensor Unit	3. Motor and Light Sensor
4. Central Control Unit (CCU)	

a. Wire Connections

Operating Procedure for Robot1:

1. Move the assembled chassis to waiting area #2.
2. Attach motor and light sensor unit to the assembled chassis.
3. Insert left track into the left hook.
4. Transport the left hook with left track to waiting area #3.
5. Insert right track into the right hook.

6. Transport the right hook with right track to waiting area #4.
7. Connect wires from station 2 to the CCU.
8. Attach gripper at station 3 (see station 3 for details).
9. Grip and insert both left and right hooks to the motorized pulley system.
10. Return to station 3 for disassembly of the gripper.
11. Push the assembled chassis with motor and light sensors into station 2 until both left and right hook converge and attach both tracks to the chassis.
12. Separate hooks from the tracks by triggering the docking sensor at station 2.

Station 3 – Gripper Assembly

Fixture Components:

1. Motorized Lift (stationary part of station 3).
2. Stationary Ramp
3. Central control unit (CCU)
    a. Wire Connections
4. Motorized Gripper

Operating Procedure for Robot1:

I. Gripper Assembly:

1. Ascend “backwards” on the ramp.
2. Turn 180° on the top of the ramp and dock into position.
3. Operate lift down until gripper slides into the front of the PR.
4. Descend “backwards” on the ramp.

II. Gripper Disassembly:

5. Ascend “backwards” on the ramp.
6. Turn 180° on the top of the ramp and dock into position.
7. Operate lift up until gripper is detached from the PR.
8. Descend “backwards” on the ramp.

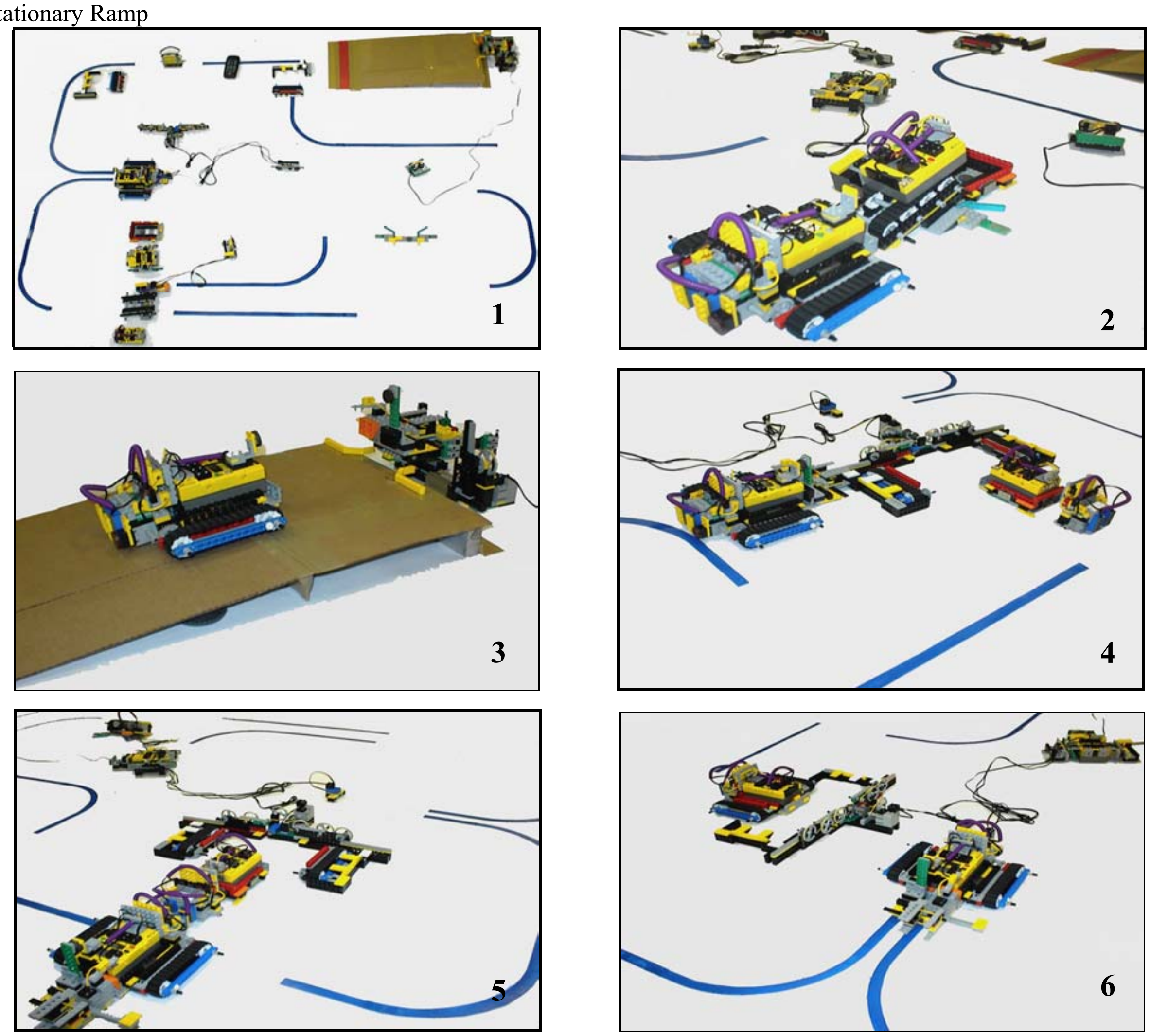

Figure 11: Replicating Process: 1) Primary robot (robot1) begins at the docking area with every part stored in the part area. 2) After assembly of station 1, robot1 pushes RCX2 onto the conveyor belt to be placed on the chassis. 3) Robot1 ascends the ramp to attach the gripper. 4) Robot1 uses the gripper to assemble station 2. 5) Robot1 pushes the RCX-chassis unit attached with the motor and light sensors onto station 2, which attaches both left and right hook to the chassis. 6) Robot1 triggers the docking sensor at station 2 to separate the hooks from the newly-assembled replica.

This procedure was conducted various times in a highly structured laboratory setting (3.75m X 3.00m in area). They were generally successful with some disparity of completion time (ranging from 45 to 75 minutes); however, there were some technical errors, such as battery failure. And, of course, due to the fact that Lego parts were used, there was frequent failure in the adjoining areas.

5. Conclusion and Discussions

Self-replication robotic systems are potentially useful in areas such as in space utilization [1-3]. The goal of our research is to create a self-replicating robotic system, which can not only replicate itself repeatedly, but also do so autonomously. We have reported the preliminary stages of our research in [18].

We have introduced basic principles of self-replicating robotics and presented a semi-autonomous replicating robotic system to illustrate an initial stage in the progress toward fully autonomous self-replicating robotic systems. Although it has yet to completely fulfill our objective of fully autonomous self-replication, it is still an important step for future work. It is expected that as more designs are conceived, new problems will arise requiring more sophisticated solutions. In the end, it will be a combination of a wide range of research areas that will allow such a system to be successfully developed.

Acknowledgements

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