Toward Self-Replicating Robots

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Abstract: In this paper we describe several prototypes of self-replicating robotic systems that have been developed at JHU. In contrast to self-reconfiguration, self-replication is the process of assembling a functional robot from passive components. The robot that is assembled (the replica) is an exact copy of the robot doing the assembling. Our presentation marks the beginning of the JHU effort in this area. The future impact of self-replicating systems is potentially enormous. In particular, the cultivation of material and energy resources in outer space using facilities built by self-replicating systems is an attractive application area worth serious consideration.

1. Introduction

In this paper we review several prototypes of self-replicating robotic systems that have been developed at JHU. In contrast to self-reconfiguration (e.g., as studied in [1-5]), self-replication is the process of assembling a functional robot from passive components. The robot that is assembled (the replica) is an exact copy of the robot doing the assembling. Such systems have the potential to revolutionize the exploitation of resources in outer space [13].

Self-replication is an essential feature in the definition of living things. At the core of biological self-replication lies the fact that nucleic acids (in particular DNAs) can produce copies of themselves when the required chemical building blocks and catalysts are present. This self-replication at the molecular level gives rise to reproduction in the natural world on length scales ranging the ten orders of magnitude from 10^{-8} meters to 10^{2} meters. Not all of the machinery involved in biological self-replication is fully understood, and remains a subject of intensive interest. Self-replication in non-biological contexts has been investigated as well, but to a much lesser degree. These efforts have resulted in the field of “Artificial Life” [10]. This field is concerned with the sets of rules that, when in place, lead to patterns that self-replicate. Such patterns are typically only geometric entities that exist inside a computer. But they do provide an existence proof for non-biological self-replication.

The concept of artificial self-replicating systems was originated by John von Neumann in the 1950's in his theory of automata. His theoretical concepts built on those of Alan Turing's “universal computer” put forth in the 1930s. The main difference was that instead of being able to read and write data, a self-replicating system reads instructions and converts these into assembly commands that result in the assembly of replicas of the original machine. The history of these ideas is discussed in [10], along with other efforts at self-replication. The vast majority of work in this area is in the form of non-physical self-replicating automata (e.g., computer viruses, the ``game of life'' computer program, etc.). The only physically-realized concepts that have been explored related to true self-replication pertain to self-assembling systems [8,9,12]. These interesting systems are collections of passive elements that self-assemble under external agitation or naturally occurring physical forces. There is no directed intention of a system to deterministically assemble a copy of itself from passive components in these physical systems, and the structures that are assembled are themselves passive.

Notable concept papers on self-replicating system for space applications were put forth in the late 1970's and early 1980's [6,11]. They proposed self-replicating factories that would weigh 100 tons each, but gave no concrete architecture, system or prototype to demonstrate the feasibility of the concept. In contrast, we discuss four self-replicating prototypes that have been developed at JHU by the authors' students in a course taught during the Spring of 2002.

2. Principle of Self-Replicating Robots

In this section self-replicating robots are categorized into two primary divisions according to their behavior. The two divisions are denoted as ``directly replicating'' and ``indirectly replicating,'' respectively. The detailed principles of these two divisions are described below. Figure 1 illustrates a diagram of how we categorize self-replicating robots.

Basically, a robot capable of producing an exact replica of itself in one generation is what we call “directly replicating”. A robot capable of producing one or more intermediate robots that are in turn capable of producing replicas of the original are called “indirectly replicating”.

2.1 Directly Replicating Robots

We classify self-replicating robots in this division into four groups according to the characteristics of their self-replication processes. The following are explanations of each self-replicating robot group.

2.1.1Fixture-Based Group

The self-replicating robots in this group depend on external fixtures in order to complete the self-replication process. Some subsystems may require high precision in positioning for assembling parts. Passive fixtures are able to assist in this because of the shape constraints that they impose. In some other cases, to unify subsystems, push-pull fixtures are helpful as well. Regardless of the particular details, fixtures serve as a substrate or catalyst to assist in 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. These subsystems are able to assist the original self-replicating robot during the assembly of the replica. This assistance can come in many forms. For instance, functioning subsystems can help in aligning, manipulating, or transporting parts.

2.1.3 Single-Robot-Without-Fixture Group

In this group only one robot is used to finish the self-replication process. Thus, the robot in this group depends only on the available environment. Usually, the complexity of the subsystems or the number of subsystems in the replica is very low for this group. This is because without fixtures or multiply cooperating robots, it is difficult to position large numbers of subsystems with high precision.

2.1.4 Multi-Robot-Without-Fixture Group

In this group more than one robot works together in the self-replication process without the assistance of fixtures. A major advantage is the reduction of the time required for self replication. A disadvantage is that there may be interference problems among robots.

There are several possible ways that a self-replicating robot can be categorized in two or three groups mentioned above. The combination of two or three different concepts can be incorporated in a potential design, such as a combining operating-subsystems-in-process with fixture-based robots. More categories are likely to be developed in the subsequent stages of our research in the area of self-replicating robots.

2.2 Indirectly Replicating Robots

The primary characteristic of the robots in this division is that the original robot or group of robots work together to build a robot-producing factory or some type of intermediate robot which is able to produce replicas of the original robot. However, the original robots lack the ability to directly assemble copies of themselves.

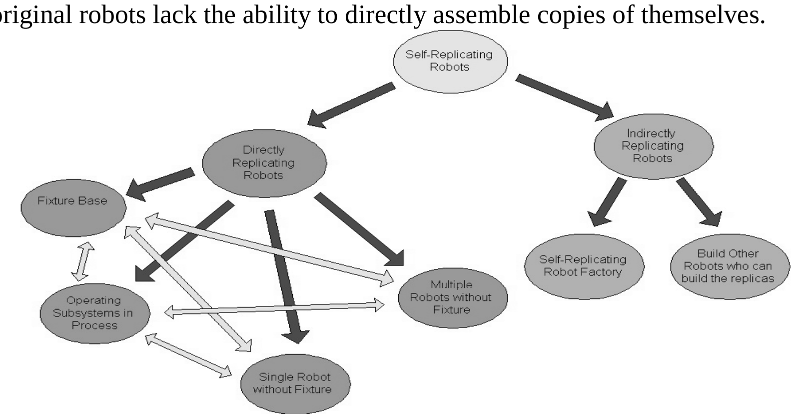

Figure 1: The Block diagram of the categorization of self-replicating robots.

3. Designs and Experiment Results

We have divided students in a Mechatronics course (taught in the Department of Mechanical Engineering at Johns Hopkins University) into eight groups to explore designs and implementations of the concept of self-replicating robotic systems. The goal of the course was for each group of students to design a robot with the ability to create an exact functioning replica of itself from a complete set of components or subsystems.

A set of rules was established to constraint students to minimize the complexity of each individual subsystem, and to encourage students to have a large number of subsystems in their design. Lego Mindstorm Kits and additional Lego parts were used in this one-semester course to reduce the building time, and invest more time in designing and testing the prototypes. The experiments were conducted in an arena made of wood sheets 1 square meter in area with walls 30 CM high. In order to focus on the mechanical issues involved in the design of self-replicating systems, the robots were remote-controlled rather than autonomous. Four of the most distinctive designs and experiments are discussed in this paper.

3.1 Robot 1: A Fixture-Based Design

The first example (denoted as “Robot 1”) consists of five subsystems (left part, right part, bumper, controller, and connector). Two fixtures are used: a ramp with constrained shape which is fitted to the controller and the connector; and a tunnel-like cave with an attached wedge on the ceiling used to physically force the connector in place. Figure 2 shows the exploded view of the Robot 1.

The process begins with the original robot dragging the right part (which consists of half of the chassis, the right wheel and the right motor) to a wall. Then the left part (which consists of half of the chassis, the left wheel and the left motor) is pushed to connect with this right part. The left and right parts of the replica are securely merged by adding the bumper which has interlocks to both subsystems. The combined subsystems are moved and oriented to a desired position and orientation next to the ramp. The original robot then pushes the controller up to the ramp, and gently drops and inserts the controller on the top of the previous combination of subsystems. The connector is fixed in its place in the same fashion. The last step is to physically force the connector to be in contact with the controller by pushing the replica in the tunnel-like area with a wedge on the ceiling. This will force the connector to be in place. After pushing the replica several times, the electronic connectors on the replica finally make contact. The replica is able to operate in the same way as the original does. Figure 3 demonstrates the self-replicating process of the Robot 1.

3.2 Robot 2: A Single-Robot-Without-Fixture Design

Robot 2 has five subsystems (left wheel system, right wheel system, left cradle, right cradle, and controller). The original robot has a pair of prongs in the front part, and uses the rear part to push the subsystems to the wall in order to compress the subsystems together. Figure 4 shows the exploded view of the Robot 2.

The process begins with the original using its prongs to move the controller to a wall. Then the robot brings one side of the cradles to insert into the slot under the controller, and pushes both parts to the wall. The first two subsystems are then connected. The other cradle is combined with the previously combined subsystems in the same way. The left and right wheel systems are then manipulated, and combined to the previously connected subsystems in a similar fashion. The replica is then able to operate. Figure 5 demonstrates the self-replication process for Robot 2.

3.3 Robot 3: Another Fixture-Based Design

This robot consists of three subsystems: the controller; the drive system; and the cage. The cage has a hinge that allows the top part of the cage to open and close to cover the wheel system and controller. The electronic connectors are attached on the top part of the cage. A passive dual linkage is hanging to assist in opening the cage. Figure 6 shows the exploded view of the Robot 3.

The process begins with the original robot pushing the cage to hook with the passive linkage, and then the top part of the cage is opened. The original robot then inserts the drive system and controller into the cage, respectively. The combined but unlocked subsystems are pushed to the wall. Because of the design of the top part of the cage, which is a curved shape, the original robot pushes the cage and the other two subsystems to the wall, and the cage is automatically closed. The replica is then completed. Figure 7 demonstrates the self-replicating process of the Robot 3.

3.4 Robot 4: A Design in which Operating Subsystems Assist in the Replication Process

In this design a subsystem is able to operate before finishing the replication process, and hence can assist in the assembly of the complete replica. Robot 4 consists of the controller, the left thread (a long wire with electronic connectors), the right thread, and the gripper subsystem. Figure 8 shows the exploded view of the Robot 4.

The process begins when the original robot uses the gripper to carry the electronic connector (attached to the long wire) to the side of the controller. Then, the original robot uses the gripper to grasp and join the electronic connector to the controller. Once finished joining the electronic connector, the left thread, connected to the end of the wire, is now functioning. A human user is now able to control this subsystem. The original robot still continues moving subsystems next to each other for the next steps. The functioning subsystem is controlled to move to a convenient location for combining other subsystems. Once the left and right threads are aligned, the original robot uses the gripper to compress and join their connectors. The gripper subsystem is a big part. From its structure the gripper is able to slide to the top of the combined left and right threads after the functioning threads are driven into a side of the gripper subsystem. Then, the original robot helps tightening the connectors. The replica is now in a fully stable and operational status. Figure 9 demonstrates the self-replication process for Robot 4.

4. Conclusion

In this paper we introduced new concepts in self-replicating robotic systems, and provided descriptions of four concrete designs that were implemented in LEGO Mindstorm kits by undergraduate students at JHU. The study of self-replicating robots is an interesting research area which has not been extensively pursued in recent years. A number of self-replicating robot designs were presented here. The different designs devised by our students has helped us to identify new research problems, and to categorize self-replicating robots. Many challenging issues remain. Our future work will be to develop truly autonomous (rather than remote-controlled) self-replicating robots.

Acknowledgments
The following is the list of students in the Mechatronics course who designed and constructed the example prototypes described in this paper. The teaching assistants for the course were Jackrit Suthakorn and Yu Zhou.

Robot 1: Jim Bankard, Oprema Ganesan, Oleg Gerovichev, Masaya Kitagawa.

Robot 2: Tabish Mustafa, Omar Rivera, Mark Sorensen, Brain Weineler.

Robot 3: James Del Monaco, Paul Stemniski, Sten-Ove Tullbery, Jason Wachs, Chris Wong.

Robot 4: Jonathan Lim, Tak Liong, Daniel Moon, Jon Tang, Vincent Wu.

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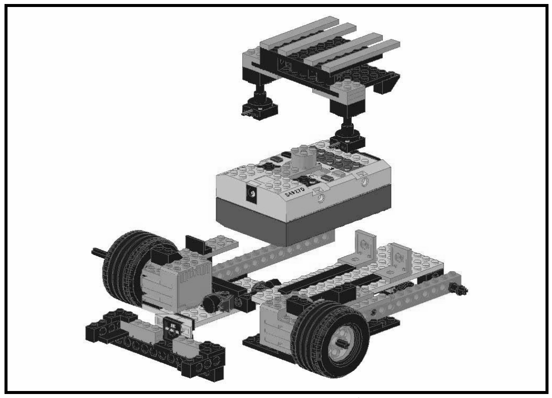

Figure 2: The Exploded View of the Robot 1.

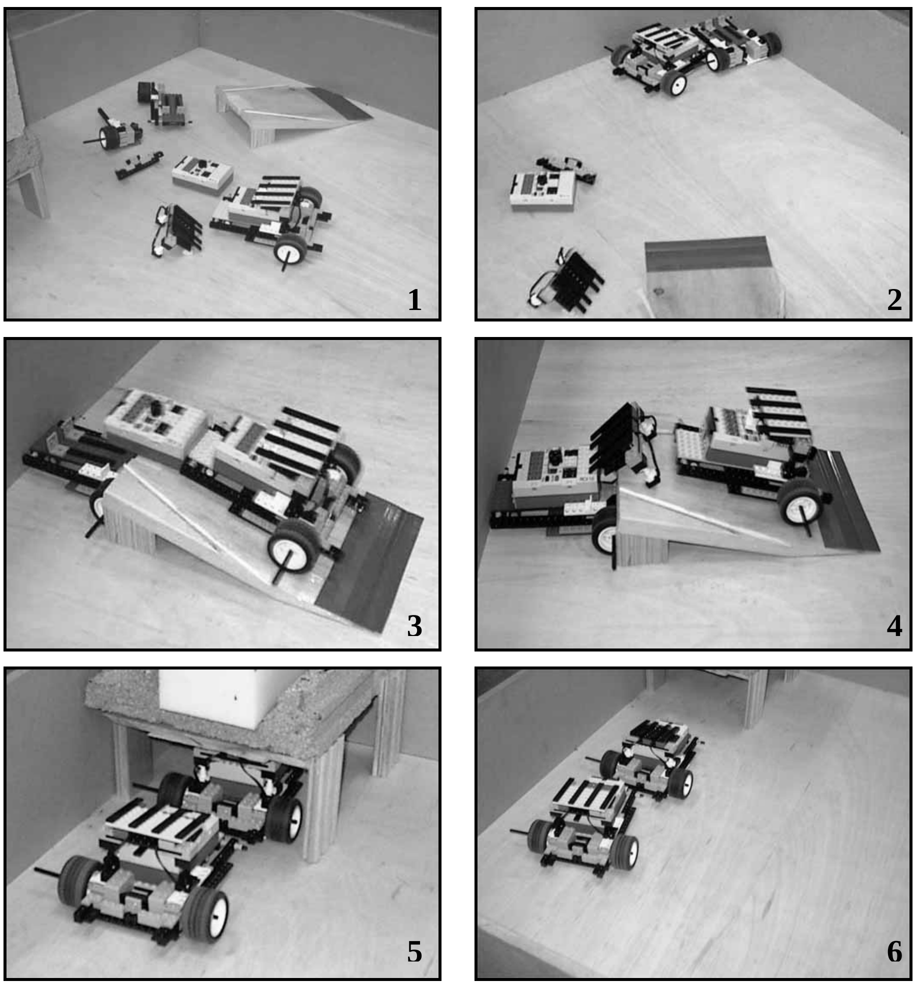

Figure 3: The Self-Replicating Process of the Robot 1.

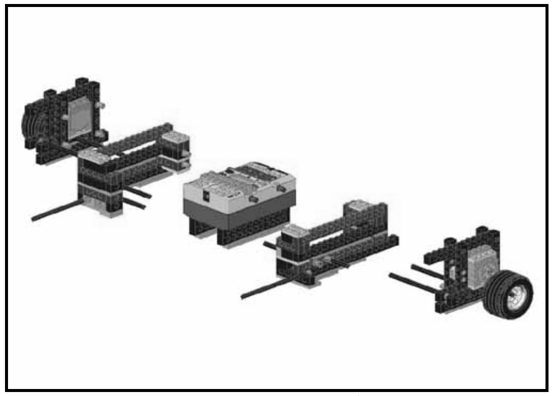

Figure 4: The Exploded View of the Robot 2.

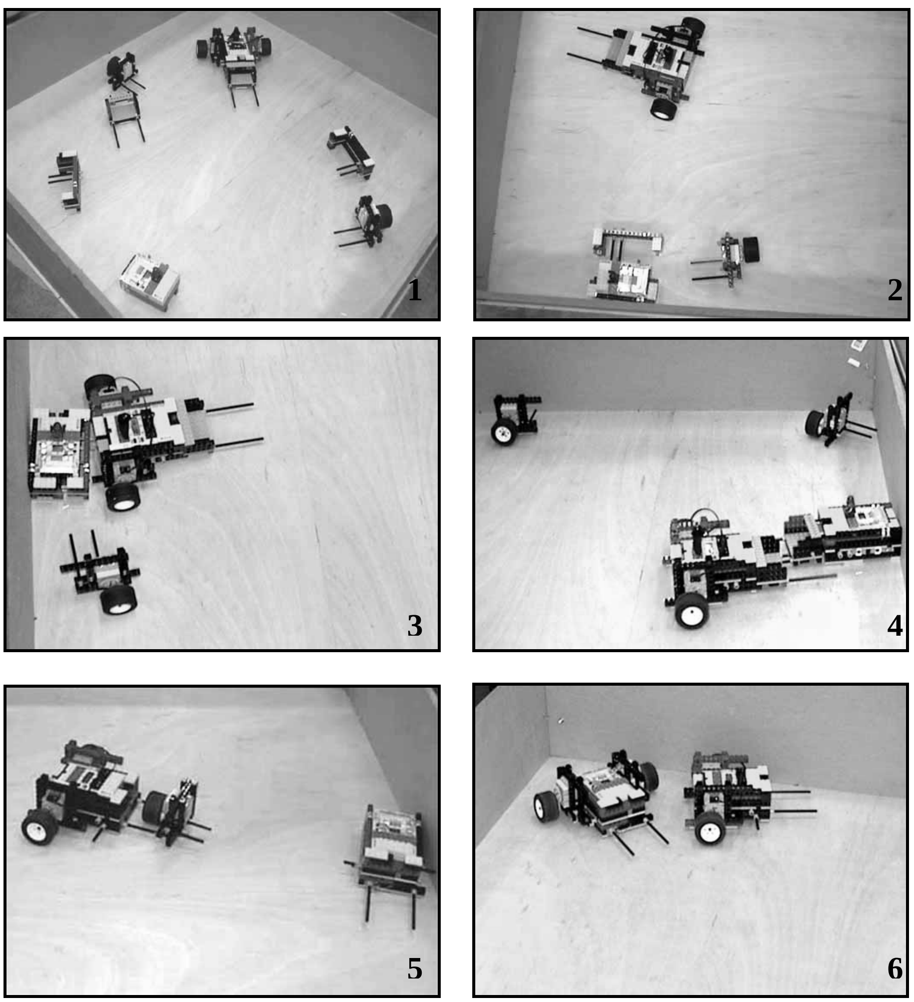

Figure 5: The Self-Replicating Process of the Robot 2.

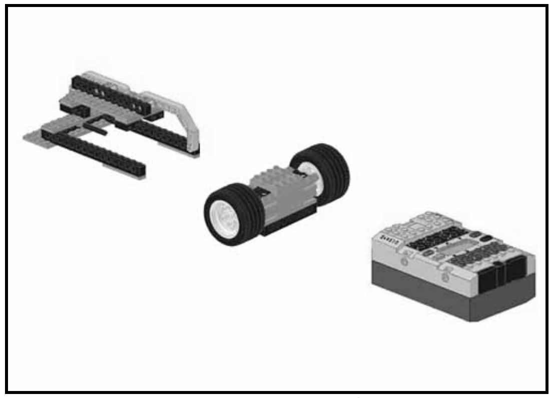

Figure 6: The Exploded View of the Robot 3.

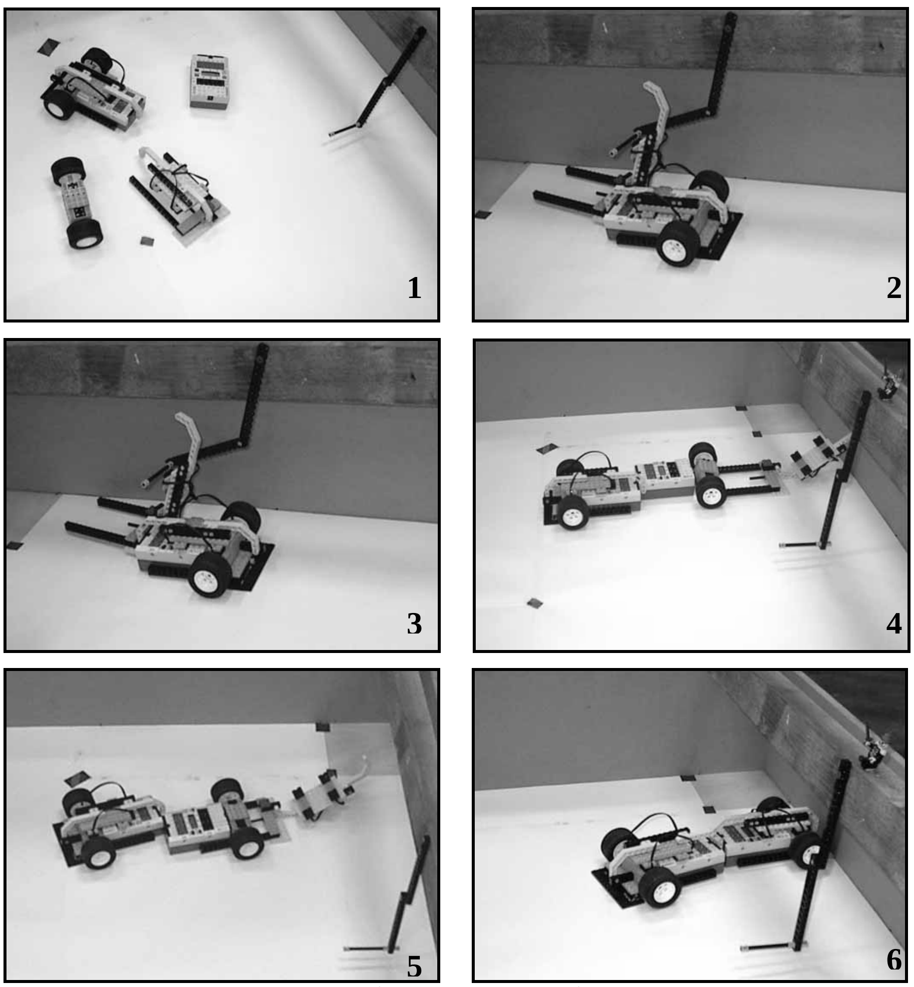

Figure 7: The Self-Replicating Process of the Robot 3.

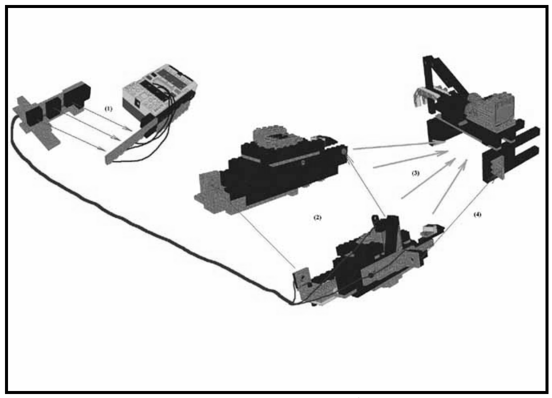

Figure 8: The Exploded View of the Robot 4.

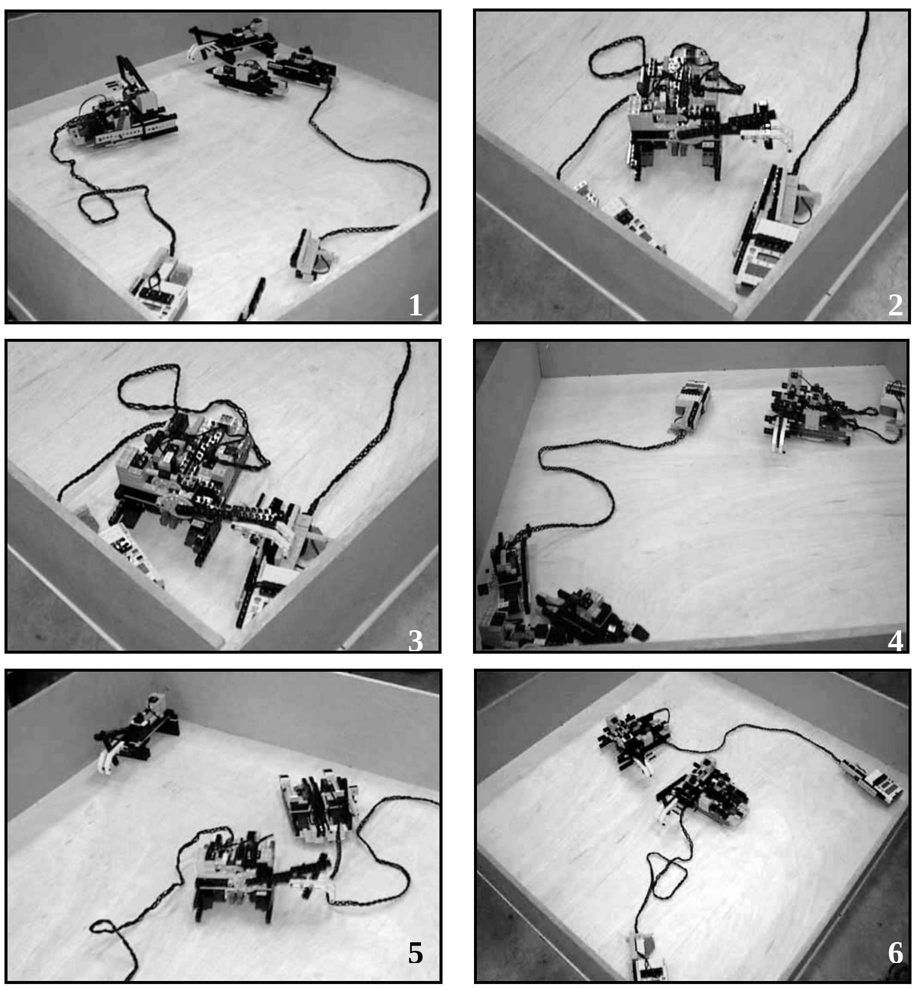

Figure 9: The Self-Replicating Process of the Robot 4.