Self-Replicating Robots for Space Utilization

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1. Motivation

Space is a potentially limitless source of materials and energy that is available for mankind's use. Unfortunately, the launch costs and environmental impact of directly sending significant numbers of humans and massive structures into outer space are prohibitive. The development of lunar resources has the potential to change this relatively grim picture. If significant portions of the lunar surface can be used for solar energy collection, and it's regolith can be effectively strip-mined and processed, then the resulting energy and materials can be transported to low-earth orbit or elsewhere in the solar system at relatively low energetic cost. This circumvents much of the energetic cost of transporting massive amounts of materials from the Earth's surface, and saves the Earth's atmosphere from the pollution resulting from unnecessary launches. The key to unlocking space resources is the autonomous development of the moon using self-replicating robotic systems that propagate over the lunar surface.

When self-replicating robotic factories take hold, the moon will be transformed into an industrial dynamo. The resulting refined materials and energy that will be produced on the moon will then provide capabilities for the exploration and colonization of space that could never exist otherwise. Equipped with refined materials and propellant derived from the moon, cultivation of other space resources will be made much easier.

The concept of artificial self-replicating systems originated with 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 [1], 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 physical self-replication pertain to self-assembling systems [2 - 4]. 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 [5, 6]. They proposed self-replicating factories that would weight 100 tons each, but gave no concrete architecture, system or prototype to demonstrate the feasibility of the concept.

Our study is motivated by these conceptual studies. However, it is important to note that to our knowledge no physically realized self-replicating robotic system has ever been built by anyone else, and to do so is one of the contributions of our research. Our vision of the central role of self-replicating robotic factories in the development of outer space is illustrated in Figure 1.

We have taken a two-pronged approach to studying self-replicating robotic systems. On the one hand, we have begun to develop robotic hardware capable of demonstrating remote controlled and autonomous self-replication in a highly structured laboratory setting. An example of our initial results is presented in the last part of Section 2. On the other hand, we have performed an analysis of how self-replicating factory systems would propagate over the lunar surface. This is summarized in Section 3. For more details of both aspects of our studies see [7, 8].

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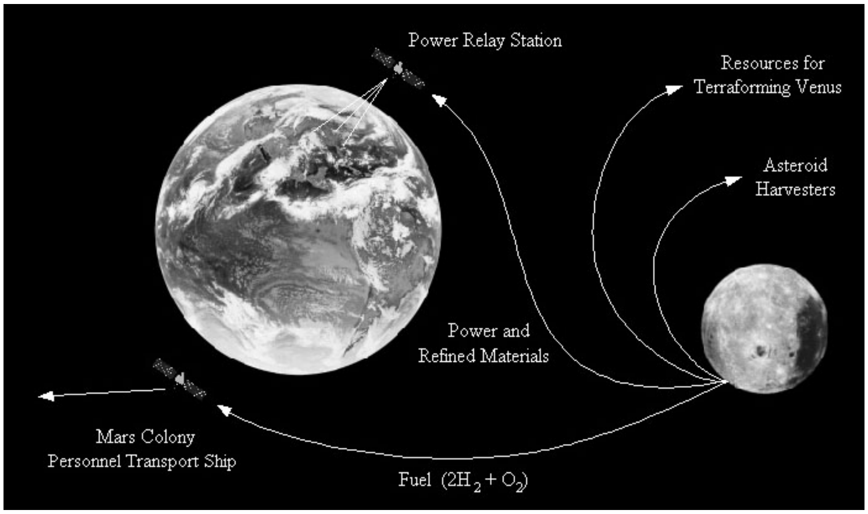

Figure 1: The Impact of Self-Replicating Lunar Factories on the Utilization of Space

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 2 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. 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.

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.

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.

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 works 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.

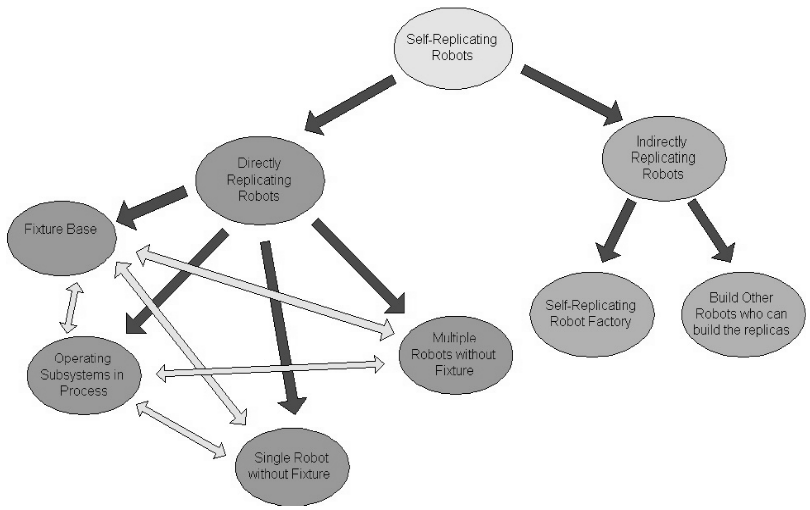

Figure 2: The Block diagram of the categorization of self-replicating robots.

A number of prototype robots is implemented by using Lego Mindstorm Kits and additional Lego parts. One example of a prototype robot is shown in Figure 3.

3. The Proliferation of Self-Replicating Robots on the Moon

Because of its significant impact on the utilization of space, we studied the proliferation of self-replicating robots on the surface of the moon. In our model, each self-replicating robotic factory consists of robots, materials processing capabilities, solar energy production, and electromagnetic railguns for transporation of replicas and materials to new locations. The proliferation process is modeled as a degenerated diffusion that evolves on the rotation group *SO(3)*. By measuring distance in units of lunar radius, the moon is approximated as a unit sphere, and the equation that describes the proliferation of self-replicating robotic systems over the surface of the moon is then [7]:

$$\frac{\partial f}{\partial t} = [d_1 X_1^R + \frac{D_{11}}{2}(X_1^R)^2 + \frac{D_{33}}{2}(X_3^R)^2] f \ . \tag{1}$$

where $f(\alpha,\beta,\gamma;t)$ is a probability density function with α, β and γ denoting the ZYZ Euler angles respectively, d_1 is the drift coefficient denoting the shooting distance per shot of the railgun, D_{11} the diffusion coefficient denoting the shooting distance error per shot in the shooting direction, D_{33} the diffusion coefficient denoting the angular shooting error per shot perpendicular to the shooting direction in the plane tangent to the lunar surface, and the time t is normalized so that t=1 corresponds to one shot. Here X_1^R and X_3^R are the differential operators

$$X_1^R = \cot\beta\cos\gamma\frac{\partial}{\partial\gamma} - \frac{\cos\gamma}{\sin\beta}\frac{\partial}{\partial\alpha} + \sin\gamma\frac{\partial}{\partial\beta} \ ; \tag{2}$$

$$X_3^R = \frac{\partial}{\partial\gamma} . \tag{3}$$

The initial condition for (1) is

$$f(\alpha,\beta,\gamma;0) = \delta(R(\alpha,\beta,\gamma)) \tag{4}$$

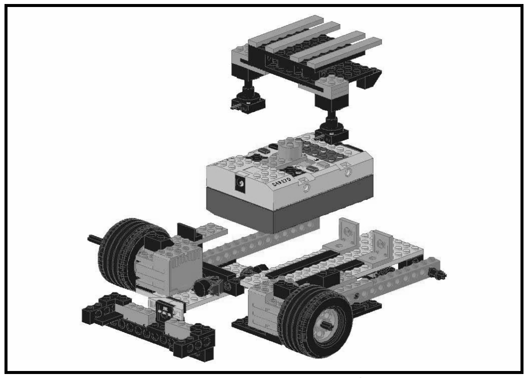

Figure 3 (a): The Exploded View of the Robot 1.

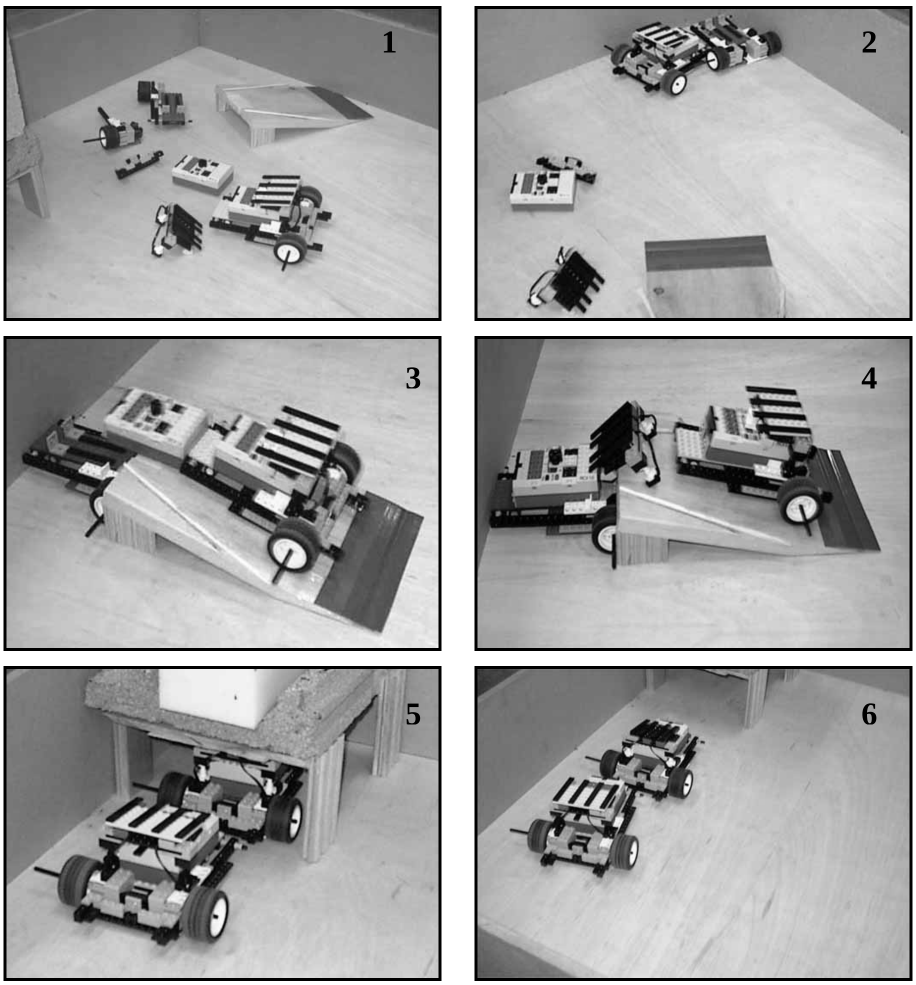

Figure 3 (b): The Self-Replicating Process of the Robot 1. Robot 1 consists of five subsystems. Two fixtures are used: a ramp with constrained shape which is fitted to the controller and the connector; and a tunnel-like cave with an attached wedge on the ceiling used to physically force the connector in place. 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.

where $\delta(R)$ is the Dirac delta function of $SO(3)$ indicating that the probability density at time zero is concentrated at the initial landing site. To study the time evolution of the probability distribution, we calculate

$$g(\alpha,\beta;t) = \frac{1}{2\pi}\int_0^{2\pi} f(\alpha,\beta,\gamma;t)d\gamma\,, \tag{5}$$

which denotes the evolution of position of self-replicating robots on the surface of the moon without regard to railgun orientation. The variables α and β serves as spherical coordinates. The following figure reflects the general process of the proliferation of self-replicating robots on the moon.

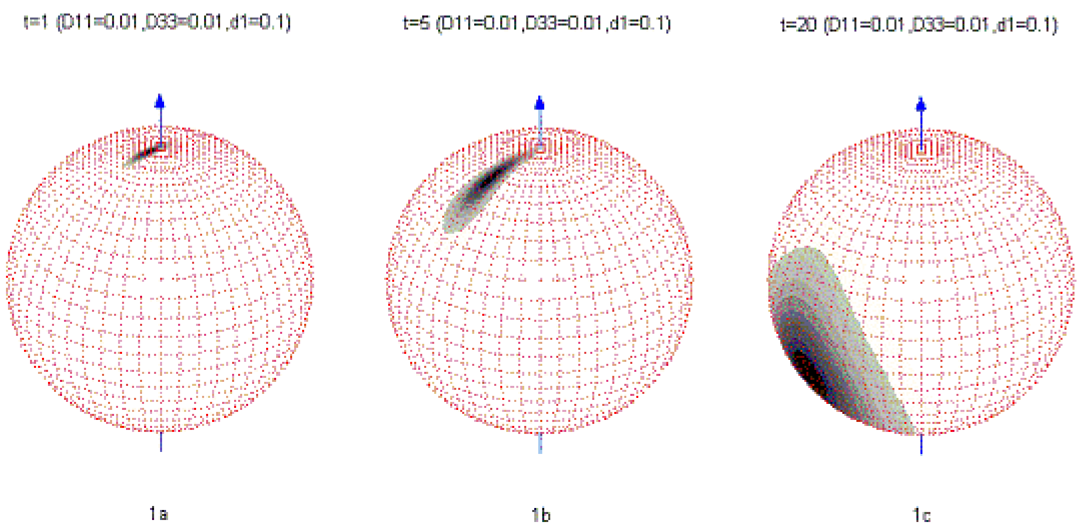

Figure 5: Evolution of Probability Distribution on the moon when D_{11}=0.01, D_{33}=0.01 and d_1=0.1. a) Probability Distribution at t=1; b) Probability Distribution at t=5; c) Probability Distribution at t=20.

4. Conclusions

Space is a domain of unlimited resources. Unfortunately, the cost of reaching space is very high. Self-replicating autonomous factories will be vital if man is to exploit space resources. Self-replicating robotic systems are a necessary ingredient for self-replicating robotic factories to become a reality.

Acknowledgments

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