Self-Replicating Robots for Lunar Development

Gregory S. Chirikjian, *Member, IEEE*, Yu Zhou, and Jackrit Suthakorn

***Abstract*—In this paper, the concept of self-replicating robots (SRRs) is reviewed, and the feasibility of a particular kind of minimalistic SRR is analyzed in the context of lunar resource development. The key issue that will determine the feasibility of this approach is whether or not an autonomous robotic factory can be devised such that it is light enough to be transported to the moon, yet complete in its ability to self-replicate with no other inputs than those resources available on the lunar surface. Self-replication leads to exponential growth, and would allow as few as one initial factory to spawn lunar production of materials and energy on a massive scale. Such capacity would dramatically impact man's ability to explore and colonize space and collect solar energy for terrestrial applications. Our concept of a self-replicating robotic factory consists of four subsystems: 1) multifunctional robots for digging and transportation of materials, and assembly of components during the replication process; 2) materials refining and casting facility; 3) solar energy conversion, storage and transmission; and 4) electromagnetic rail guns for long-distance transportation (for example, for sending materials to low-earth orbit (LEO), or transporting replicated factories to distal points on the moon). Each of these subsystems is described in the context of current technologies, with an emphasis on 1). We build on previous concepts for self-replicating systems, present a simple prototype that demonstrates active mechanical replication, and develop an analytical model of how the proliferation of such systems on the lunar surface would occur.**

***Index Terms*—Artificial life, degenerate diffusion, lunar resources, moon, proliferation, robot, rotation group, self-replication.**

I. Introduction and Motivation

THIS SECTION provides the context in which to view our work. Section I-A examines the history and state of the art in self-replicating systems, and provides motivation for our study of self-replicating robotic factories for the exploitation of lunar resources. Section I-B examines the impact that self-replicating lunar factories would have on the exploration and colonization of space, as well as the impact that such a system would have on the availability of clean energy for use on the earth. Section I-C reviews the material resources available on the lunar surface, and points to specific material processing technologies to refine these resources, and how these resources may be used effectively.

The remainder of the paper then is structured as follows. Section II discusses our design concept for a self-replicating lunar factory; Section III concentrates on the robotic elements of this factory and discusses toy prototypes with which we have performed experiments; and Section IV models how self-replicating factories would spread on the moon as a function of several design parameters.

A. Past, Present, and Future of Self-Replicating Systems

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. Self-replication in nonbiological contexts has been investigated as well, but to a much lesser degree. These efforts have resulted in the field of "artificial life" [45]. This field is concerned with sets of rules that, when in place, lead to patterns that self-replicate. Such patterns are typically only geometric/algorithmic entities that exist inside a computer. But they do provide an existence proof for nonbiological self-replication.

The concept of artificial self-replicating systems was originated by von Neumann in the 1950s in his theory of automata. His theoretical concepts built on those of 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 together with a copy of the assembly instructions (so that the replica also has the ability to replicate). The history of these ideas is discussed in [45], along with other efforts at self-replication. The vast majority of work in this area is in the form of nonphysical self-replicating automata (for instance, computer viruses, the "game of life" computer program, etc.). The idea of self-replicating software for metamorphic robots has been investigated recently in [3], which could be an important step in physical self-replication.

However, the only physically realized concepts that have been explored related to self-replication pertain to self-assembling systems [33], [39], [42], [52]. 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 it is difficult to imagine that such concepts could be put to use in attaining the goal of energy and materials production on the moon (which is our motivation for studying this subject).

Notable concept papers on self-replicating system for space applications were put forth in the late 1970s and early 1980s [17], [50]. 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. Our study is motivated by these conceptual studies. However, it is important to note that to our knowledge no deterministic self-

Manuscript received March 31, 2002; revised October 1, 2002. Recommended by Guest Editors W.-M. Shen and M. Yim. The work presented in Section IV of this paper was supported by the National Science Foundation (NSF) under Grant ITS 0098382.

The authors are with the Department of Mechanical Engineering, Johns Hopkins University, Baltimore, MD 21218 USA.

Digital Object Identifier 10.1109/TMECH.2002.806232

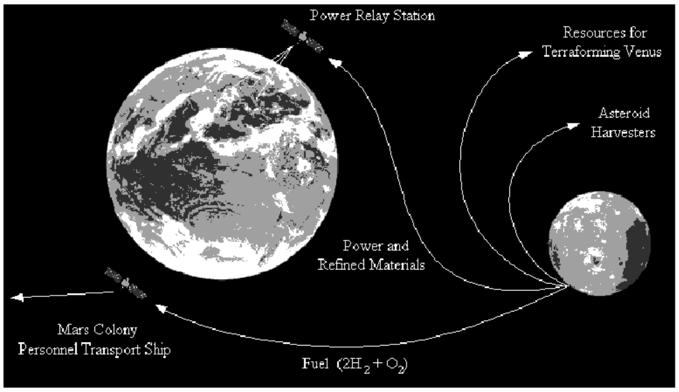

Fig. 1. Potential impact of self-replicating lunar factories on the utilization of space.

replicating mechanical/robotic system has ever been built by anyone else, and to do so is one of the contributions of this paper. Our vision of the central role of self-replicating robotic factories in the development of outer space is illustrated in Fig. 1.

Our interest in self-replicating robots arose as an extension of our previous work on modular self-reconfigurable robots and cellular robotic systems. Self-reconfigurable, or metamorphic, robots have been investigated by a number of authors [5]–[7], [15], [18], [24], [26], [28], [36], [38], [44], [47], [53]–[55]. In most of these efforts, the modular components are all connected in some way (either physically or by a communications link), and the topology of that connection changes as a function of time based on the task requirements. In self-replicating systems, one or more functional robots assemble copies of themselves. The replicas may then act together as a swarm, or not. Recently, a related concept with a totally different implementation, called self-extending machines, has been introduced, where robots evolve from basic building blocks using rapid manufacturing technology (see [32] and references therein).

B. Impact of Self-Replicating Robots in Space and on Earth

Space is a potentially limitless source of materials and energy that is available for mankind's use. Space robotic systems for planetary exploration have attracted attention (for example, [13]). Unfortunately, the launch costs and environmental impact of directly sending significant numbers of humans and massive structures into outer space are prohibitive. The U.S. heavy-launch capability has not increased in the past 20 years, and is not likely to change in the next 20. In fact, the U.S. heavy-launch capability is currently inferior in many ways to what it was 30 years ago (i.e., we currently do not have the ability to put a man on the moon at will). New technologies such as horizonal take-off and horizonal landing "aerospace planes" will make access to low-earth orbit (LEO) more accessible during the next 20 years, but will not solve the problems associated with launching massive amounts of material beyond LEO.

The development of lunar resources over the period 2020–2040 has the potential to change this relatively grim picture. If significant portions of the moon 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 LEO 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 reduces the atmospheric pollution that would result from unnecessary launches.

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. For instance, it has been estimated that there are 6.6 million tons of ice trapped in the south polar region of the moon [16]. If this water can be harvested, then the constituent hydrogen and oxygen will make an excellent energy storage medium for use in fuel cells and/or rocket propellent. The hydrogen can also be used to reduce metal oxides in the lunar regolith to extract and purify the large amounts of silicon, iron, and aluminum that exist [43].

The ideas proposed here will have tremendous positive impact on the earth's environment for a number of reasons. Solar energy collected on the moon could be beamed to satellites in LEO, and redirected to collection sites on earth. One potential technology to implement this is to use microwaves [31], [37], [40]. Refined materials transported to LEO from the moon could be used to construct these relay satellites or to construct a network of massive satellites to partially shield the earth from the sun, thus reducing the greenhouse effect.

In short, efficient use of the moon may be the most practical way to have favorable impact on the earth's environment over the next 50 years. But the moon's resources cannot be exploited in a practical way by directly launching massive production facilities there. Hence, self-replicating systems are essential.

C. Composition of the Moon: Resources Worth Developing

Of course, for self-replicating lunar factories to be useful, the material inputs must be available for the systems to self-replicate and spin off both solar panels and construction materials to be sent to LEO or elsewhere.

The development of lunar resources including the harvesting of solar energy has been investigated for many years (see, for example, [1] and [23]), and the generation of solar power on the moon remains of interest today [10]. An important architecture that would almost certainly have to be integrated into ours for the concept of self-replicating robotic factories to succeed is that of *in situ* production of photovoltaic solar cells. This has already been studied by others; for example, see [12], [25], and [30].

The most abundant elements in the lunar regolith (as a percentage of the total number of atoms) are [43], [46]

Elements	Mare	Highland	Average
Oxygen	60.3 ± 0.4	61.1 ± 0.9	60.9
Silicon	16.9 ± 1.0	16.3 ± 1.0	16.4
Aluminum	6.5 ± 0.6	10.1 ± 0.9	9.4
Calcium	4.7 ± 0.4	6.1 ± 0.6	5.8
Magnesium	5.1 ± 1.1	4.0 ± 0.8	4.2
Iron	4.4 ± 0.7	61.1 ± 0.9	60.9
Sodium	0.4 ± 0.1	0.4 ± 0.1	0.4
Titanium	1.1 ± 0.6	0.15 ± 0.08	0.3

Trace elements in the lunar regolith (in grams/cubic meter) include [21], [23], [43]

Sulfur	1800
Phosphorus	1000
Carbon	200
Hydrogen	100
Nitrogen	100
Helium	20
Neon	20
Argon	1
Krypton	1
Xenon	1

These tables indicate that all the materials essential for building structures, motors, electronics, propulsion, and energy harvesting/storage are present on the lunar surface.

II. Specific Design Concept

The central idea of this paper is a specific concept of self-replicating robotic system for energy and materials production on the moon. The key components of this proposed system are as follows:

1) *Multifunctional Robots*. These are robots capable of assembling copies of themselves given a complete set of unassembled parts. These robots, which we envision consisting of a mobile platform as a base with attached manipulation devices, will not only assemble replicas of themselves but also be used for assembly of the subsystems listed below from their components. With the addition of a suite of tool fixtures, these robots will also be used for mining and local transportation of materials and components between subsystems within the small region of the lunar surface occupied by one factory site (which we envision to be approximately one km^2).
2) *Materials Refining and Casting Facility*. This is a subsystem that will take in the strip-mined lunar regolith (sand), melt it using energy from subsystem 3 (described below), and separate the oxygen from the silicon, aluminum, and iron oxides that are plentiful in the regolith. These molten materials will then be separated and fed into molds formed from sintered regolith. The resulting castings will then serve as the components of new copies of all of the subsystems listed here.
3) *Solar Energy Conversion, Storage and Transmission*. Both photovoltaic cells and solar radiation that is reflected and concentrated with mirrors can be used. Photovoltaic cells would power the robots, rail gun (see below), and electrolytic separation of elemental metals from oxides in the materials processing plant. Recent work by others has demonstrated the feasibility of using lunar resources for solar energy production (for example, [10]). The energy generated by one factory will by design be far in excess of the energetic requirements of the factory's own self replication. The excess energy could be transmitted to low-earth-orbiting satellites using microwaves. One key issue is energy storage. If sufficient water or elemental hydrogen exists, this will not be a problem because fuel cells will be an option. In the absence of these resources, two alternatives exist. One would be not to store energy at all, but rather only use energy as it is produced. A second option would be to maintain elemental metals in a molten state, and use these as fuel cell material, which when oxidized with the previously separated oxygen, would produce electricity.
4) *Electromagnetic Rail Guns*. These would be used for long-distance transportation (for example, for sending materials to LEO, or transporting replicated factories to distal points on the moon). In this concept, when a replica is ready to be transported to a new location, all of its subsystems would be packed into an iron casing, and accelerated much like a bullet train. It would then be shot ballistically like a cannon ball until it lands at its new location. If the scale is made large enough, the same guns could shoot materials directly to LEO. Since a rail gun consists of many repeated identical units, and since the gun's role does not occur during the replication process, there is no need to send a whole rail gun to the moon. Only one section need be sent. A mold of this section would be constructed *in situ*, and this section would be replicated to construct the full rail gun.

Our specific architecture that proposes to integrate these constituent systems is described in Fig. 2. The arrows in this figure represent actions or the transfer of resources between subsystems. The key for this overall system to be self-replicating is the interior closed loop indicating robot self-replication when casted robot parts are made available. This is labeled as "self-replication process" in Fig. 2. Here the "robot manipulator" is what is known as a *mobile manipulator* in the robotics community [11], [19], [27], [35]. It is a mobile robot with attached manipulator devices such as arms and/or grippers. It is not just a fixed manipulator arm.

An example of what one factory replica might look like is shown in Fig. 3.

III. Self-Replicating Robots

Multifunctional self-replicating robots are a key component in making the concept of this paper practical. This is reflected in Fig. 2, where the inner loop from robots back onto robots (robotic reproduction of robots from refined components) induces the self-replicating character of the overall system. In short, without robotic self-replication, there would be no self-replicating energy and materials production capability in this model. For this reason, we consider in some detail in this section the desirable characteristics of self-replicating robots, and demonstrate potential design concepts using toy models.

A. What Exactly Does it Mean for a Robot to be Self-Replicating?

Before we begin investigating design criteria for self-replicating robots, it is essential that an acceptable working definition of self-replication be given. At first, this would seem to be an easy matter. One could simply say that a self-replicating robot is a robot that can be reproduced by one or more robots of the same kind. However, the complicating issue is, from what is the

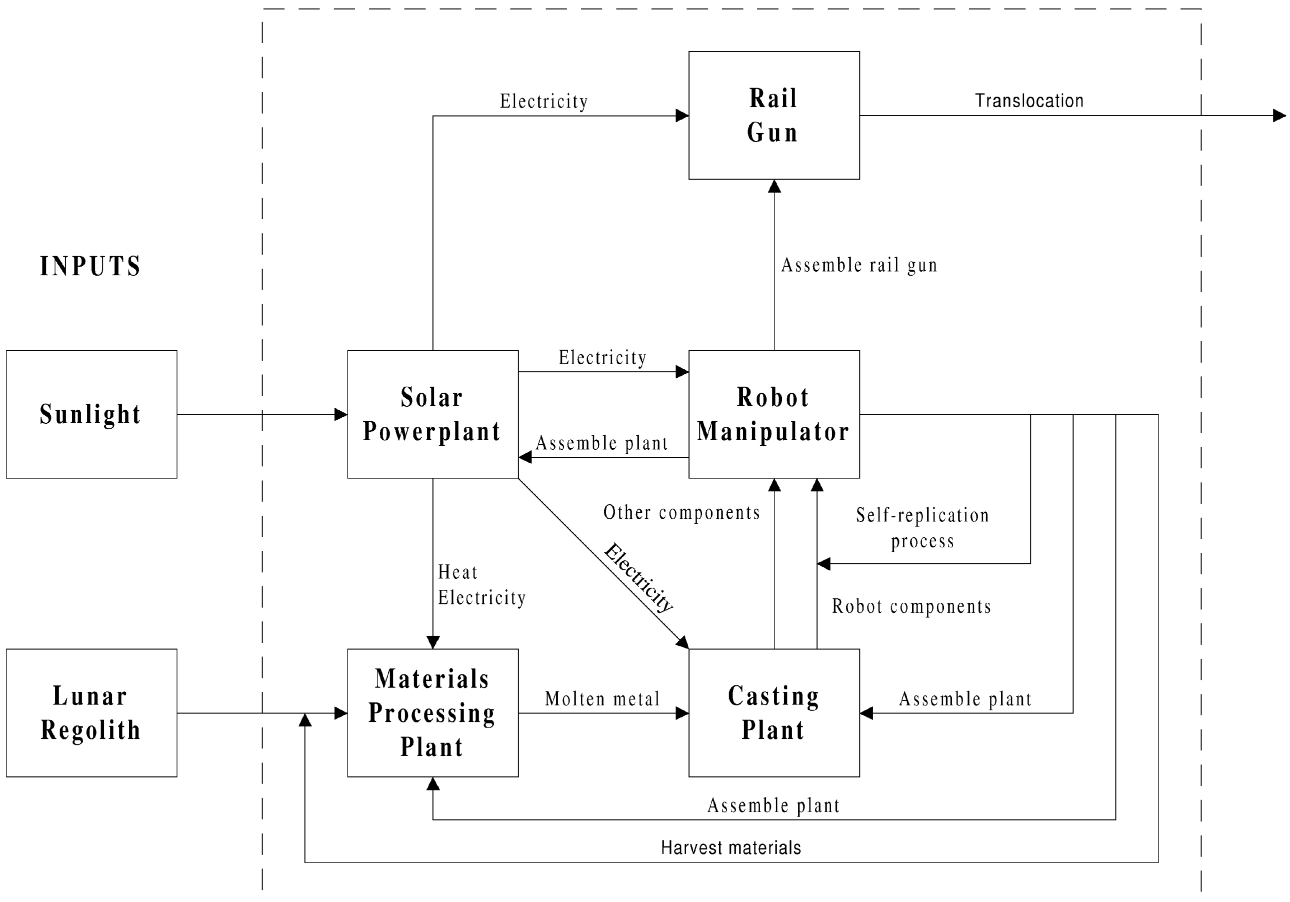

Fig. 2. Architecture for self-replication.

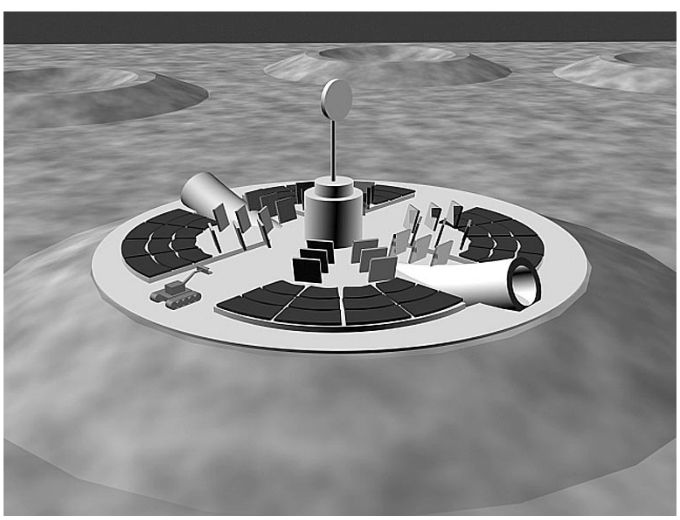

Fig. 3. Depiction of the functioning system.

robot reproduced? This issue goes back to von Neumann himself [45], in which he argued that an automaton operating in a sea of spare parts could assemble copies of itself. However, what does it mean to be a spare part? Is a six degree-of-freedom manipulator a spare part? Is a direct drive dc motor a spare part? Is an aluminum cylindrical rod a spare part?

For the purpose of this discussion, we will assume that any rigid object produced by the casting plant is an acceptable starting point. This eliminates sweeping under the rug the details of how articulated or actuated components come into existence. If they are to be used in the construction of the robot, then the robot must be able to assemble these articulated or actuated components from rigid components of castable shape using abundant lunar resources. This is true for computing as well as mechanical components. If one is going to produce microprocessors in a self-replicating plant, then the ability to reproduce a microprocessor factory must be factored in. Needless to say, for our concept to remain as simple as possible, the robot concept explored here will not rely on the use of a microprocessor.

The tricky balance is that the more complex the system is, the greater the infrastructure must be in order for it to be a self-replicating system. This is true in biology as well, where the infrastructure that gave rise to systems as complex as the human brain evolved over billions of years aided by random mutations and natural selection. On the other hand, a system must be of sufficient complexity that it can perform self-replication. This is an active undertaking of the robot that is somewhat more difficult than passive self-assembly of components that has been successfully demonstrated elsewhere.

In the context of the application at hand, the goal is modest: Design a simple self-replicating robot that (perhaps in collaboration with other robots of the same kind) will assemble a replica of itself from rigid components with geometric features that can be produced by casting molten material in a mold. While this method of component manufacturing is not the only one, it is easy to imagine that castings can be used to make new molds, and the new molds can in turn make new castings. Hence, this method of component production lends itself to overall system self-replication. In contrast, another manufacturing technique such as laser sintering could be imagined, but this would require the ability to reproduce a laser. No such need exists for casting.

In the subsections that follow, we examine in detail the mechanical and electronic/computational paradigms that are appropriate for this concept.

1) Mechanical Design Principles: In order for a robotic system to have sufficient ability to replicate itself, obtain natural resources through digging, assemble other components of the overall system, and have some tolerance to errors, the following design criteria will be observed:

- robots must have the ability to independently locomote on a two dimensional (2-D) surface that deviates from an ideal plane;
- robots should have adaptable rigid fixtures for each task;
- actuators of the robots must consist of rigid subunits, each of which can be assembled by simple motions;
- robots must be able to transport solid objects (i.e., all components for which it is responsible for assembly) and a volume of powder to any desired position and orientation in the plane, and transport their payload to a height above that plane;
- overall design must be compact and light weight in order for it to be feasible for the initial system to be transported to the moon, and for replicas to be shot to new locations on the moon.

The reasons for these criteria are clear. Satisfying them will result in a robot capable of the sorts of tasks required for self replication as well as mining and construction.

2) Easily Manufactured Actuators: An essential aspect of the concept of self-replicating robotic factories is the ability of robots, and/or fixed automation systems, powered by certain kinds of actuators to be able to assemble actuators of the same kind from passive rigid elements. These rigid elements would be the castings produced by the materials refining plant. While actuator design and assembly using *in situ* resources may at first appear to be difficult, they are not insurmountable problems. Electromechanical actuators such as dc brush motors could be constructed using either permanent magnets made from elemental nickel or iron, or various alloys or rare-earth materials mined from the moon. As an alternative, the stator of a motor could be purely electromagnetic with its magnetic field induced by the flow of current through a coil of metal. This coil could either be coated with a metal oxide to serve as insulation, or simply be designed so that the coil does not contact any other component, hence, removing the possibility of a short circuit. The rotor assembly could be several iron castings of convex shape that are held together with rings at both ends. Each iron casting could be surrounded by aluminum coils. The aluminum coils would be insolated from the iron castings and from each other with sintered metal oxides. Crude bushings and brushes for such motors are also not difficult to imagine.

Perhaps the simplest actuation technology is the solenoid. Here only an external helical conducting coil, presumably made from aluminum, is required. When energized, such a coil can cause a spring-loaded iron or nickel push rod to be pulled in. When unactuated, the spring returns the push rod to its original length. This kind of "binary" actuator has been studied by the authors extensively in their previous work on high-degree-of-freedom manipulators.

The actuation issue is in many ways closely related to the manufacturability of the rail gun and the idea of electromechanical intelligence (proposed in the next subsection). If one core technology, such as solenoids, can address all three issues, this would reduce the number of different issues that need to be explored within the concept of a lunar self-replicating robotic factory.

3) Self-Replicating Intelligence: In order for a system of the kind considered here to become a reality it must either be the case that the computing power behind the intelligence is quite limited, or that control inputs in the form of physical computing elements (or remote-control commands) are sent from earth. Our concept follows the first tack, which ensures the true self-replicating nature of the system. This is consistent with what happens in the natural world. Lower life forms such as bacteria replicate without intelligence as defined in the traditional sense. And biological viruses, which are usually not even characterized as living organizms, are capable of astonishingly complex results, such as the manufacture of self-assembling capsid proteins, even though they have quite simple genetic codes.

Looking to biology for motivation, we take a minimalist approach to the intelligence aspects of self-replicating robotic factories. Instead of sophisticate microprocessors (which are sensitive to radiation) each robot brain could consist of electromechanical switches, primitive vacuum tubes (without the need for actual glass tubes due to the vacuum of space) and metal ticker-tape as a data storage medium. These ideas are in line with several modes of thought in the robotics community in the past decade. For instance, Brooks' subsumption architecture [2] is based on a reactive behavior in which sensory data drives robot motion. In Wiener's classic work, he also mentioned a simple mobile robot which implemented steering using a very simple control unit: a bridge consisting of two photoelectric cells [51]. The work of Tilden on robots capable of surprisingly complex behavior with central control units consisting of a few transistors [22] also encourages us to pursue this direction. Canny and Goldberg [4] explored the idea of minimalism in robotics. This built on the work of Mason and Erdmann [14], [34] who argued that physical objects contain inherent information that can be explored with simple sensors and maneuvers when the designer incorporates his or her knowledge of mechanics into the robot.

These are very much the philosophies that are employed here. Since it is highly unlikely that the capacity will exist in the next 20 years to boost a fabrication plant for high-end microprocessors beyond LEO, and since constant transportation of microprocessors from earth to moon would be almost as cumbersome as remote controlling the robot from the earth, we consider here the minimal intelligence criteria that the robot must satisfy. The criteria are

- robots must translate encoded instructions into tasks consisting of moving objects and exerting forces;
- robots must be able to sense and correct their location relative to artificial landmarks;
- robots must be able to assess if they are damaged, misassembled, and/or not functioning properly;
- robots must be able to identify all components for which they are responsible to manipulate;
- robots must transfer all of the above abilities to their replicas.

We believe that all of these tasks can be achieved using networks of large electromechanical relays rather than microelectronics. That is to say, previous works in which small numbers of transistors are used to implement robots capable of complex behaviors can easily be extended to the case where very robust electromechanical relays replace the function of the transistors.

Note that over time the tasks which the robots are to perform do not change. Hence, if their mechanics, sensing, and task execution capabilities are well though out from the beginning, there is no need for re-programmability.

As an initial step in the direction of developing self-replicating robots, we have breadboarded prototypes that demonstrate the robotic self-replication issues. These are described in the following subsection.

B. Prototypes

This subsection describes several prototypes of self-replicating robots to demonstrate the feasibility of the inner replication loop in Fig. 2. In order to focus on the mechanical issues involved in the design of self-replicating systems, the prototypes are designed to be remote controlled or partially autonomous systems. Additionally, to further reduce the complexity of the experiments, we use LEGO Mindstorm kits, along with enhanced electrical connections and magnetic alignments to build our subsystems because of their ease of use and modularity. In [9] we divided self-replicating robots into several groups based on the characteristics of their self-replication processes and illustrated these groups with robots built by our undergraduate students. Here, we illustrate prototypes in two of these categories with new prototypes that have not been described before.

1) Prototype 1—A Fixture-Based Design: Prototype 1 is a remote-controlled robot, consisting of seven subsystems: the left motor, right motor, left wheel, right wheel, microcontroller receiver, manipulator wrist, and passive gripper. This particular implementation is not autonomous. We built it to demonstrate that it is mechanically feasible for one robot to produce a copy of itself. In this design, several passive fixtures are located in the assembly area to assist the robot to assemble a replica. In other words, the robot depends on these external passive fixtures for self-replication. These external fixtures are not actuated and are manipulated by the original robot. The original robot is remotely controlled to relocate those subsystems from a storage area to the assembly area, and the original robot is then guided to perform the assembly process as follows.

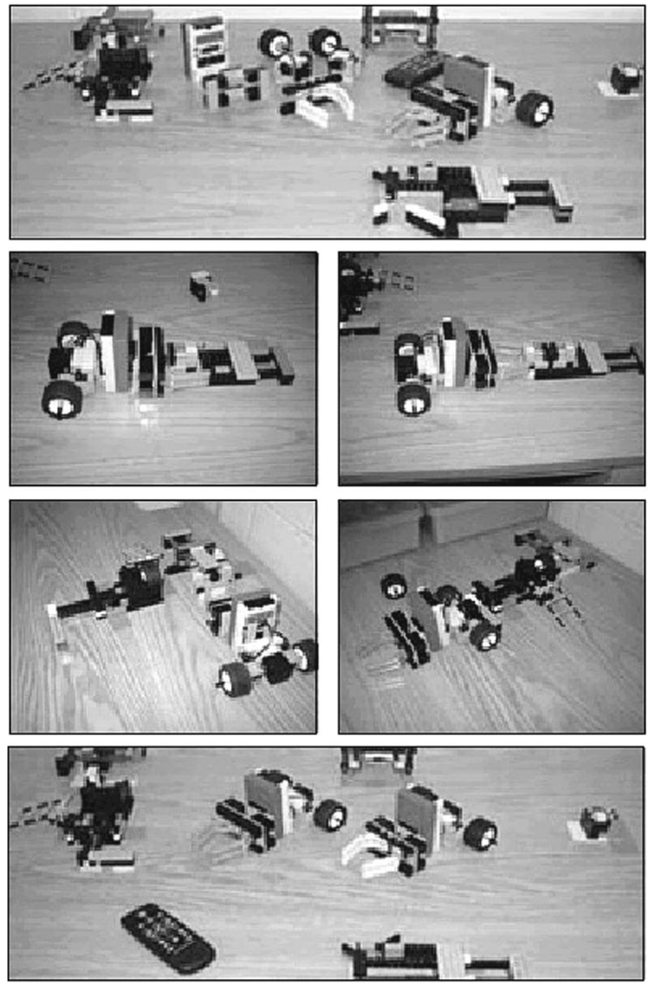

Fig. 4. Replication process of prototype 1.

The original robot retrieves the left motor subsystem from the storage area and slides it into a motor assembling fixture (this fixture is designed to have a narrow slot so that when the motors are placed in it, they are forced to align with each other). The robot then moves the right motor subsystems from the storage area into the motor-assembling fixture. After both left and right motors are aligned in the fixture, the robot exerts pressure on the subsystems so that they snap together and form one piece. The original robot then manipulates the motor-assembling fixture so as to release the motor subsystem, which completes the first stage of assembling the subsystems. The robot then takes this motor subsystem and slides it into a wheel-assembling fixture which is designed to assist attaching the left and right wheels to the subsystem. After the wheels are successfully attached to the motor subsystem, the robot manipulates the wheel fixture to release the assembled part. The robot continues to perform procedures similar to the previous steps to relocate parts and assemble them. The process leads to the completion of a replica of the original robot. Sample pictures from the experiments are shown in Fig. 4.

2) Prototype 2—A Semi-Autonomous Replicating System: This design has different characteristics from the one mentioned

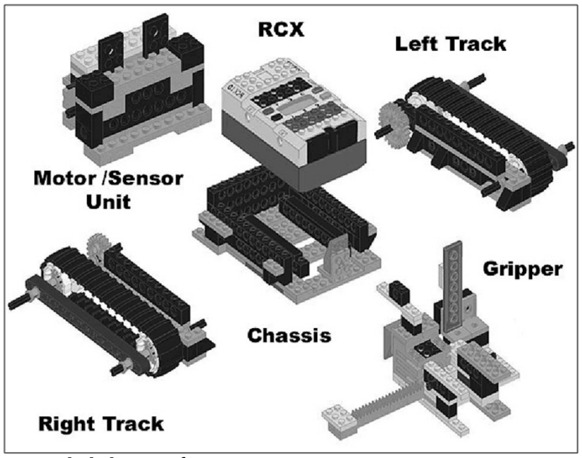

Fig. 5. Exploded view of prototype 2.

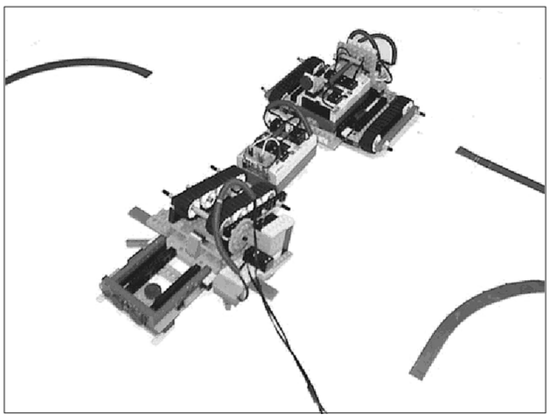

Fig. 6. Station 1.

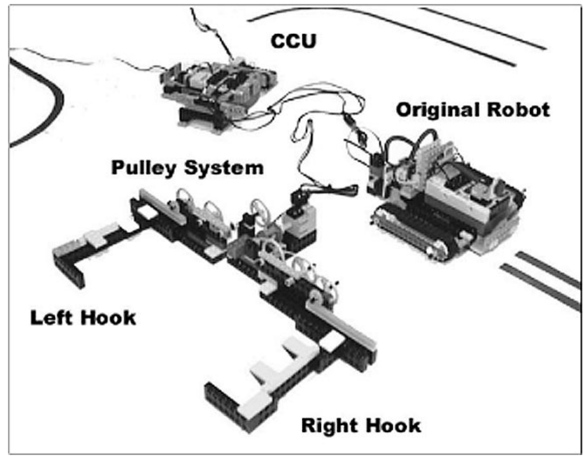

Fig. 7. Station 2.

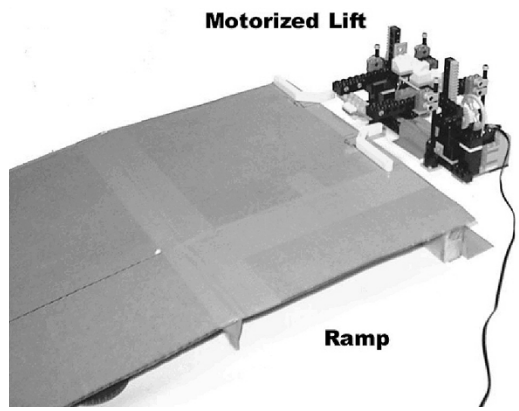

Fig. 8. Station 3.

above. In this concept, the original robot is unable to make copies of itself directly. The robot therefore needs to make intermediate systems with different properties than itself. The intermediates are then able to assist the original robot in manufacturing replicas of the original.

This prototype system is based on our previous results in remotely controlled robotic replication with additional features that enable the robot to perform many subtasks in the replication process autonomously. This is an important step in the development of fully autonomous self-replicating robots.

Prototype 2 requires three assembly stations as intermediate systems. These three stations are: 1) chassis assembly station; 2) motor and track assembly station; and 3) gripper assembly stations. In our implementation all these stations are actuated, autonomously activated and assembled by the original robot.

Prototype 2 and each assembly station are described here in the order of the replication process. Prototype 2 consists of five subsystems: robot control system (RCX), chassis, left track, right track, and motor/sensor unit. Fig. 5 illustrates all the components of prototype 2. With lines drawn on the floor between the three stations, a robot is able to commute autonomously between stations along the lines without any human input. It then acts under remote control at each station. Hence, this system is semiautonomous.

Station 1 (chassis assembly station) consists of four subsystems: conveyor-belt/sensor unit, docking unit, electrical connector, and central controller unit (CCU). Fig. 6 illustrates Station 1. The conveyor-belt/sensor unit connects to the docking unit and the CCU via an electrical cable, which provides the electrical power and control. Station 1 combines the RCX with the chassis. Station 1 automatically starts to work when the chassis is aligned with the assembly position by the original robot. The feedback system powers the conveyor-belt to assemble the RCX to the chassis.

Station 2 (motor and track assembly station) consists of left and right hooks, CCU, electrical connector, stationary docking sensor, and motorized pulley unit. Fig. 7 shows Station 2. To establish Station 2, the original robot uses the gripper obtained from Station 3 to align and insert the hooks into the pulley unit which is fixed and driven by a LEGO motor with differential gears and two sets of reduction gear/belt systems. Station 2 assembles the left and right tracks to the RCX-chassis assembly. At first, the original robot moves the tracks into the hooks. Then the robot combines the motor/sensor unit to the assembly from Station 1, and moves it to Station 2. Station 2 is activated when the light-sensor located in the middle of the pulley unit detects the assembly. Then, the hooks push the tracks to attach to the assembly. The original robot proceeds to the docking area and triggers the hooks to release the finished replica.

Station 3 (gripper assembly station) consists of a CCU, an electrical connector, a ramp and a lift system used to move the gripper up and down. Fig. 8 illustrates Station 3. Station 3 attaches a motorized gripper arm to the original robot. The gripper

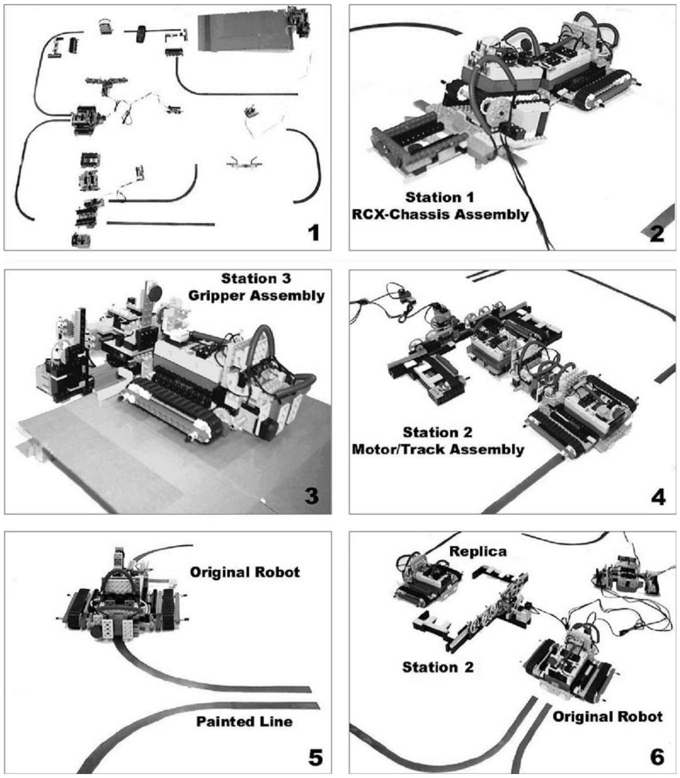

Fig. 9. Replication process of prototype 2.

is an example of an interchangeable tool of the robot. A motor is used to drive a rack and pinion system to open and close the jaws of the gripper. The original robot moves onto the ramp to dock into position. To attach the gripper, the lift operates down until the gripper slides onto the front of the robot. To detach the gripper, the lift operates up until the gripper separates from the robot. Fig. 9 shows sample pictures of the replication process.

Although this system has yet to fulfill our objective of fully autonomous self-replication, it is still a major stepping stone for future work. It is expected that as more designs are conceived, new problems will arise requiring more sophisticated solutions. Such a fully autonomous self-replicating system might employ a combination of geometric constraints with proper placement of magnets, which is analogous to the artificial self-replicating molecules proposed by Rebek [41].

IV. Proliferation of Self-Replicating Robots on the Moon: An Analysis

In this section, a mathematical model of the proliferation of self-replicating robotic factories on the surface of the moon is presented. The purposes of this model is not to analyze the growth in the number of robots. Rather, it illustrates how errors in the rail gun shooting direction would influence the evolution of factory locations. By knowing this, one is in a better position to determine how accurate and intelligent the self-replicating systems must be in order to perform their functions. Section IV-A models the spreading of self-replicating factories as a degenerate diffusion that evolves on the rotation group $SO(3)$. Section IV-B presents analytical and numerical solution results that can be used to evaluate different strategies for covering the moon with self-replicating robots, and how these strategies impact design decisions.

A. Model of Proliferation as a Degenerate Diffusion

The moon is approximated well as a sphere. If we measure distance in units of lunar radius, then the moon is a unit sphere. Any point on a unit sphere can be described by first introducing a right-handed coordinate frame fixed to the sphere at its center. Then, an arbitrary point is obtained by first rotating the natural unit basis vector $\mathbf{e}_3$ by an angle β counterclockwise around the $\mathbf{e}_2$ axis, followed by a rotation around the inertial $\mathbf{e}_3$ axis by an angle α. This puts the vector at the position

$$\mathbf{u}(\alpha,\beta) = ROT\,[\mathbf{e}_3,\alpha]\,ROT\,[\mathbf{e}_2,\beta]\,\mathbf{e}_3 = \begin{pmatrix} \cos\alpha\sin\beta \\ \sin\alpha\sin\beta \\ \cos\beta \end{pmatrix}. \tag{1}$$

Here, we have used the notation $ROT[\mathbf{n},\theta]$ to represent counter-clockwise rotation around unit vector $\mathbf{n}$ by angle θ.

In the current context, it is not sufficient to describe the evolution of self-replicating robots by only considering their position on the moon. Since the mode of transportation for these robots between distal locations will be by rail gun, the orientation of this gun in the plane tangent to the lunar surface becomes critical. The combination of position on a sphere and an additional angle, γ, which represents an orientation about $\mathbf{u}(\alpha,\beta)$, means that the complete pose of a robot/factory/rail gun system on the lunar surface is described by the 3×3 rotation matrix

$$\begin{aligned} R(\alpha,\beta,\gamma) =& ROT[\mathbf{u}(\alpha,\beta),\gamma]ROT\,[\mathbf{e}_3,\alpha]\,ROT\,[\mathbf{e}_2,\beta] \\ =& ROT\,[\mathbf{e}_3,\alpha]\,ROT\,[\mathbf{e}_2,\beta]\,ROT\,[\mathbf{e}_3,\gamma]\,. \end{aligned} \tag{2}$$

We can interpret this rotation matrix as having all the relevant information about the position and orientation of one robot/system. The position vector $\mathbf{u}(\alpha,\beta)$, pointing to a particular robot/system from the center of the moon, is the third column of $R(\alpha,\beta,\gamma)$. Likewise, $\mathbf{n}(\alpha,\beta,\gamma)$, which describes the direction in which the rail gun points, can be taken to be the first column. Hence, we write

$$R(\alpha,\beta,\gamma) = [\mathbf{n}, \mathbf{u}\times\mathbf{n}, \mathbf{u}]. \tag{3}$$

If a rail gun has an expected shooting distance of $0 < d_1 \ll 1$ measured in units of lunar radius, then a new robot/system will be shot from location $\mathbf{u}$ to a new location

$$\mathbf{u}' = ROT\,[\mathbf{u}\times\mathbf{n}, d_1+\epsilon_1]\,\mathbf{u} \tag{4}$$

where ϵ_1 is a small stochastic error that would depend on the terrain conditions at both sites, the performance of the gun, fluctuations in magnetic and gravitation fields between the two sites, etc. If ϵ_1 were the only error in the process, the orientation of the new rail gun would be

$$\mathbf{n}' = ROT\,[\mathbf{u}\times\mathbf{n}, d_1+\epsilon_1]\,\mathbf{n} \tag{5}$$

if the new gun is constructed tangential to the same great arc that the old one was. This is the simplest strategy because the only landmark that would be formed if a pod containing a replica factory were shot to a new location would be a skid mark on the lunar surface pointing in a direction normal to $\mathbf{u} \times \mathbf{n}$. The direction of such a skid mark could easily be detected using primitive machine intelligence, and used as a que for establishing the direction of the new rail gun replica.

Of course, there will be some deviation in the orientation of the new rail gun relative to this ideal direction due to construction errors, etc., and so the new orientation will actually be described by

$$\mathbf{n}'' = ROT\left[\mathbf{u}', \epsilon_2\right]\mathbf{n}'. \tag{6}$$

If we assume that the errors ϵ_1 and ϵ_2 are uncorrelated Gaussian white noises

$$\epsilon_1(t)dt = \sqrt{D_{11}}dw_1(t) \tag{7}$$
$$\epsilon_2(t)dt = \sqrt{D_{33}}dw_2(t) \tag{8}$$

then the equation that describes the proliferation of self-replicating robotic systems over the surface of the moon is[56]

$$\frac{\partial f}{\partial t} = \left[d_1 X_1^R + \frac{D_{11}}{2}\left(X_1^R\right)^2 + \frac{D_{33}}{2}\left(X_3^R\right)^2\right] f \tag{9}$$

where $f = f(\alpha, \beta, \gamma; t)$ is a time-evolving probability density function, and α, β, and γ are ZYZ–Euler angles. Here, d_1 is the drift coefficient in units of the lunar radius, which has a physical meaning of the shooting distance per shot; D_{11} is a diffusion coefficient in units of lunar radius, which has a physical meaning of the shooting distance error per shot in the shooting direction; D_{33} is a diffusion coefficient in units of lunar radius, which has a physical meaning of the angular shooting error per shot perpendicular to the shooting direction. Moreover, the time t is normalized so that $t = 1$ corresponds to one shot. The differential operators X_i^R have the explicit form [8]

$$X_1^R = \cot\beta\cos\gamma\frac{\partial}{\partial\gamma} - \frac{\cos\gamma}{\sin\beta}\frac{\partial}{\partial\alpha} + \sin\gamma\frac{\partial}{\partial\beta} \tag{10}$$
$$X_2^R = -\cot\beta\sin\gamma\frac{\partial}{\partial\gamma} + \frac{\sin\gamma}{\sin\beta}\frac{\partial}{\partial\alpha} + \cos\gamma\frac{\partial}{\partial\beta} \tag{11}$$
$$X_3^R = \frac{\partial}{\partial\gamma}. \tag{12}$$

The initial conditions for (9) are written as

$$f(\alpha, \beta, \gamma; 0) = \delta(R(\alpha, \beta, \gamma)) \tag{13}$$

where $\delta(R)$ is the Dirac-delta function for $SO(3)$ indicating that the probability density at time zero is concentrated at the initial landing site and initial rail gun orientation, which together define $R = I_3$ (the 3×3 identity matrix).

B. Solving the Degenerate Diffusion Equation

To solve (9), we expand f in an $SO(3)$-Fourier series as

$$\begin{aligned} f(R) &= \sum_{l=0}^{\infty}(2l+1)\sum_{m=-l}^{l}\sum_{n=-l}^{l}\hat{f}_{nm}^l U_{mn}^l(R) \\ &= \sum_{l=0}^{\infty}(2l+1)\text{trace}\left[\hat{f}^l U^l\right] \end{aligned} \tag{14}$$

where

$$\hat{f}_{mn}^l = \int_{SO(3)} f(R) U_{mn}^l\left(R^{-1}\right) d(R) \tag{15}$$

and R denotes a member of $SO(3)$ and $d(R)$ is the volume element at R [8]. Here, U^l is a $(2l+1)\times(2l+1)$-dimensional matrix called an irreducible unitary representation of $SO(3)$ with $l = 0, 1, 2\ldots$ [20], [48], [49]. Its elements are given by

$$U_{mn}^l\left(R_{ZYZ}(\alpha, \beta, \gamma)\right) = e^{-im\alpha}P_{mn}^l(\cos\beta)e^{-in\gamma} \tag{16}$$

where $|m|, |n| \le l$, and the functions $P_{mn}^l(\cos\beta)$ are generalizations of the associated Legendre functions [49].

Then, we use the facts that [8], [20], [49]

$$X_1^R U_{mn}^l = \frac{1}{2}c_{-n}^l U_{m,n-1}^l - \frac{1}{2}c_n^l U_{m,n+1}^l \tag{17}$$
$$X_2^R U_{mn}^l = \frac{1}{2}ic_{-n}^l U_{m,n-1}^l + \frac{1}{2}ic_n^l U_{m,n+1}^l \tag{18}$$
$$X_3^R U_{mn}^l = -inU_{mn}^l \tag{19}$$

where $c_n^l = \sqrt{(l-n)(l+n+1)}$ for $l \ge |n|$ and $c_n^l = 0$ otherwise.

Hence, application of the $SO(3)$-Fourier transform to (9) and corresponding intial conditions reduces (9) to a set of linear time-invariant ODEs of the form

$$\frac{d\hat{f}^l}{dt} = \mathcal{A}^l\hat{f}^l \text{ with } \hat{f}^l(0) = I_{2l+1}. \tag{20}$$

Here, I_{2l+1} is the $(2l+1)\times(2l+1)$ identity matrix and $\mathcal{A}^l$ is a banded matrix with elements that are independent of time.

The solution for each value of l is the matrix exponential

$$\hat{f}^l(t) = e^{t\mathcal{A}^l} \tag{21}$$

which is substituted into the Fourier inversion formula (14) to find $f(R, t)$. After we do this, the evolution of positions occupied by self-replicating robots on the surface of the moon (without regard to rail gun orientation) is obtained by computing

$$g(\alpha, \beta; t) = \frac{1}{2\pi}\int_0^{2\pi} f(\alpha, \beta, \gamma, t)d\gamma. \tag{22}$$

Integration over γ allows us to visualize the propagation over the sphere.

C. Numerical Results

By using Fourier analysis on the rotation group SO(3), we solve the partial differential equation to get the function $g(\alpha, \beta, t)$, and draw the pictures of the probability distribution at different values of time.

Here, different sets of parameters are chosen in order to compare their impact on the probability distribution and its evolution. Based on the proposed operation on the moon, reasonable values for each parameter are chosen, and plots are generated to reflect the time evolution of the probability distribution of where the latest generation of self-replicating factories will be dispersed. In order to study the time evolution of the probability distribution, we use the deviation from the uniform distribution, which is defined as

$$C(t) = \sqrt{\int_0^{2\pi}\int_0^{\pi}\left(g(\alpha, \beta, t) - \frac{1}{4\pi}\right)^2 \sin\beta d\beta d\alpha} \tag{23}$$

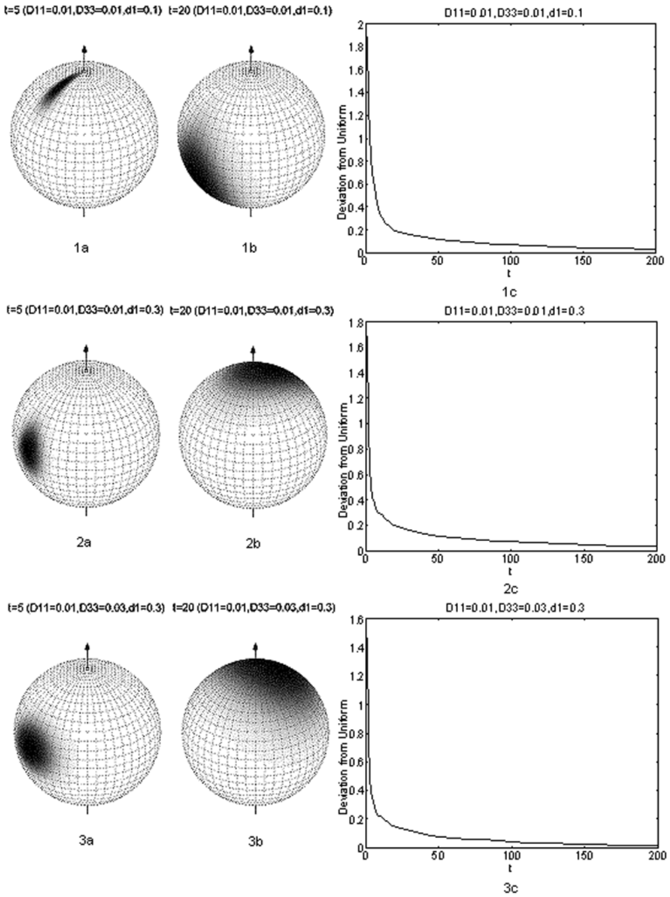

Fig. 10. Probability distribution on the sphere. a) Probability distribution when $D_{11} = 0.01$, $D_{33} = 0.01$, and $d_1 = 0.1$. b) Probability distribution when $D_{11} = 0.01$, $D_{33} = 0.01$, and $d_1 = 0.3$. c) Probability distribution when $D_{11} = 0.01$, $D_{33} = 0.03$, and $d_1 = 0.3$.

where the uniform distribution on the sphere has the fixed value of $1/4\pi$.

Comparing Fig. 10(a) and (b), one can see that with other parameters fixed, a change in the drift coefficient d_1 causes the probability distribution to drift at a different speed. Apparently, the larger the drift coefficient is, the faster the dark area moves on the sphere. This is because a larger drift coefficient means a longer shooting distance. Comparing Fig. 10(b) and (c), one can see that with other parameters fixed, a change in the diffusion coefficient D_{33} causes the probability distribution to spread out at a different speed. Apparently, the larger the diffusion coefficient is, the bigger the dark area is at the same time t. This is because a larger diffusion coefficient means a larger shooting error, which results in a wider possible area of scattering.

From Fig. 10, one can also see that as time goes on, the probability distribution converges to the uniform distribution on the sphere. Moreover, larger parameter values cause a quicker convergence of the probability distribution to the uniform distribution.

This analysis leads to the result that a noisy rail gun may have desirable properties with regard to the dispersion of self-replicating factories. This kind of analysis is a first step in the optimal specification of subsystem properties.

V. Conclusion

A concept for simple self-replicating robotic systems composed of mobile robots, materials processing unit, solar panels and a rail gun is explored in this paper. The goal of such a system would be to exploit the material and energy resources that are present on the earth's moon both for use on earth and for the exploration and utilization of outer space. The feasibility of such a system is analyzed in terms of availability of resources on the moon, and the impact on the design of self-replicating systems to take advantage of those resources. Initial hardware prototypes constructed from LEGO Mindstorm kits that demonstrate directed replication (which is a key step in developing autonomous self-replicating systems) are described, and their function is evaluated. Videos of these systems' function can be found on our webpage http://custer.me.jhu.edu. An analysis of the proliferation of self-replicating robots on the surface of the moon is also presented.

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Gregory S. Chirikjian (M'93) was born on August 16, 1966 in New Brunswick, NJ. He received the B.S.E. degree in mechanical engineering, the M.S.E. degree in mechanical engineering, and the B.A. degree in mathematics from The Johns Hopkins University, Baltimore, MD, in 1988, and the Ph.D. degree from California Institute of Technology, Pasadena, in 1992.

Since the summer of 1992, he has been with the Department of Mechanical Engineering, The Johns Hopkins University, where he is currently a Professor. His research interests include the kinematic analysis, motion planning, design, and implementation of biologically inspired robots. In particular, "hyper-reduntant," "metamorphic," and binary" manipulators, and most recently self-replicating robots. In recent years, he has also been applying methods from robotics to model conformational transitions in biological macromolecules.

Dr. Chirikjian is the recipient of a 1993 National Science Foundation (NSF) Young Investigator Award, a 1994 Presidential Faculty Fellow, and a 1996 ASME Pi Tau Signa Gold Medal.

Yu Zhou received the B.S. and M.S. degrees in mechanical engineering from Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 1992 and 1997, respectively. Currently, he is working toward the Ph.D. degree in mechanical engineering at The Johns Hopkins University, Baltimore, MD.

His research interests include stochastic modeling of dynamic systems, robot motion planning, and inverse problems in engineering.

Jackrit Suthakorn was born in Thailand on May 24, 1973. He received the B.E. degree in mechanical engineering from Mahidol University, Bangkok, Thailand, in 1995 and the M.S. degree in mechanical engineering from Michigan Technological University, Houghton, in 1998. He is currently working toward the Ph.D. degree at The Johns Hopkins University, Baltimore, MD.

His research interests include self-replicating robots, service robots, binary robots, and kinematic analysis of hybrid serial-parallel mechanisms.