An Architecture for Self-Replicating Lunar Factories

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Summary of Phase I Results

The purpose of this project was to analyze the feasibility of an automated robotic factory system for the in-situ development of lunar resources. The ultimate goal of such a system is to make resources available for construction of a lunar colony and the transportation of refined resources to low-lunar or low-Earth orbit for construction of large spacecraft. Our proposed architecture for accomplishing this goal consisted of five subsystems: (1) multi-functional robots for digging and transportation of materials, and assembly of components during the replication process; (2) materials refining plant; (3) parts manufacturing facility; (4) solar energy conversion, storage and transmission; (5) Electromagnetic guns for long-distance transportation (e.g., for sending materials to low-Earth orbit, or transporting replicated factories to distal points on the moon).

The key issue to determine the feasibility of this approach in the NIAC time frame was whether or not complementary technologies expected over the next 10 to 40 years would exist for an autonomous robotic factory to function. In particular, it was not clear a priori whether such a system could be devised such that it would be small enough to be transported to the moon, yet complete in its ability to self-replicate with little input other than what is available on the lunar surface. The situation regarding projected US heavy-launch capability has been dramatically changed with the initiative put forth by President George W. Bush. But even in light of this new initiative, minimalist systems which can be launched at low cost, harvest lunar resources, and bootstrap up to a substantial production capability are appealing. 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, as well as to deliver hydrogen and oxygen to fuel interplanetary spacecraft and the fledgling industries that will develop in space over the next few decades.

Many technological hurtles must be overcome before self-replicating robots can become a reality, and current knowledge from many diverse disciplines must be recombined in new ways. In this Phase I feasibility study we examined what lunar resources can be exploited, and investigated "toy" designs for robots with the ability to self-replicate. To this end, we examined how each subsystem of a robotic factory (motors, electronic components, structural elements, etc.) can be constructed from lunar materials, and demonstrated these ideas in hardware. We did this at several

levels. For example, robots that assemble exact functional copies of themselves from pre-assembled subsystems were demonstrated; The feasibility of assembling an actuator from castable shapes of structural material and molten metal was demonstrated with proxy materials; The assembly of simple self-replicating computers made of individual logic gates was demonstrated; A strategy was developed for how the lunar regolith can be separated into ferrous, nonferrous conducting, and insulating materials in the absence of water was studied and partially demonstrated. In addition, the energy resources available at the lunar surface were evaluated, means for using this energy were developed, and the energetic requirements of various subsystems were computed. Our conclusion is that the proposed system architecture indeed appears to be feasible provided certain existing technologies can be integrated in new ways. Phase I focused on the selection, demonstration and analysis of individual technologies for each subsystem in the architecture. Phase II will focus on the integration of these technologies, physical demonstration at the system level, and additional analysis.

The objectives which were achieved during Phase I had never been achieved by others, despite substantial theoretical interest in self-replicating systems over the past fifty years. Over the two years preceding the Phase I award, the PI's research group established the infrastructure necessary to successfully meet the objectives of the proposed work. As follow-on to this work which further builds on this infrastructure, a phase-II proposal will seek to examine aspects of the broader architecture by implementing each part of the proposed factory architecture as a model subsystem and demonstrate the functionality of the integrated system.

Organization of This Report

Section 1 presents an introduction and history of the topic of self-replicating systems and the relationship of past efforts to our advanced concept description. This section also discusses the impact that implementation of this concept would have on man's exploration and colonization of space. Section 2 reviews the specific architectural details and aims of the Phase I effort. These first two sections provide both the big-picture description of our concept, as well as reviews of relevant materials, manufacturing and energy production technologies to establish the feasibility of the proposed architecture. Previous studies on self-replicating systems are described, and the lack of concrete principles, designs and implementations in self-replicating robotic systems is observed. Section 3 discusses how time was allocated during the effort. Section 4 explains how prior work done by others can be integrated into our concept. Section 5 is a detailed discussion of lunar resources and processing technologies. Section 6 focuses on mechanical design requirements for constructing robots and simple computers from parts that can be manufactured in situ. Section 7 evaluates the mass requirements for an initial precursor that could be launched to initiate the bootstrap process up to the full factory level. Section 8 provides an analysis of the energy requirements and means for harvesting energy. Section 9 examines how to design robust systems with minimalist intelligence from relays that can be manufactured in situ. Section 10 provides an analysis of the proliferation of self-replicating factories on the lunar surface.

Novel prototypes developed by the PI's students are described in the reports and draft manuscripts appended at the end of this report. While these materials are presented as appendices, they represent some of the major novel contributions developed under this work. Namely, they represent the first functional self-replicating robot prototypes and the first demonstration of a transistor circuit which can make a copy of itself using the paradigm of self-replication by self-inspection. These phase I prototypes reflect the philosophy that the best way to demonstrate feasibility is by building a "toy" model. Videos of all of these systems can be found on the webpage: http://custer.me.jhu.edu.

1 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. 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" [76, 129]. 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 [76, 129], 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.) [86, 113, 130]. Molecular and nanotechnology also uses ideas of self-replication and self-assembly (see e.g. [92]) but it is difficult to see how such ideas might be implemented for the goal of lunar resource utilization. And while robots are often used as examples to motivate the study of self-replicating systems (see e.g., Figure 1), the technical issues that need to be resolved to make self-replicating robots a reality are very different than those addressed by theoreticians.

The only physically-realized concepts that were explored in the first 50 years of research on self-replication related to self-assembling systems [104, 63, 120, 143, 87]. These interesting systems are collections of passive elements that self-assemble under external agitation or naturally occuring physical forces. There is no directed intention of a system to deterministically assemble a copy of itself from passive components

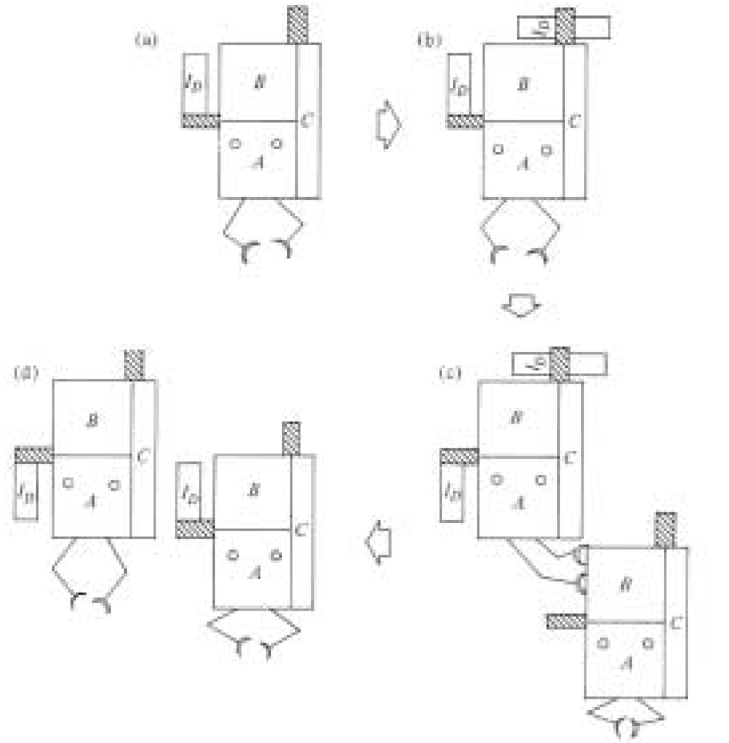


Figure 1: Transfer of Code in a "Fanciful" Self-Replicating Robot. A Perspective from Theoretical Computer Science (Figure reprinted with permission from M.A. Arbib [2])

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. Therefore, we have undertaken the task of evaluating and developing self-replicating technologies which can make full use of lunar resources. Such resources may be used to achieve a variety of goals as depicted in Figure 2. However, the development of these scenarios is beyond the scope of this Phase I NIAC study.

Notable concept papers on self-replicating system for space applications were put forth in the late 1970's and early 1980's [43, 140]. They proposed self-replicating factories that would weigh 100 tons each and evaluated materials processing and manufacturing technologies available at that time, but produced no concrete system or prototype to demonstrate the feasibility of the concept. Our work is motivated by these conceptual studies. However it is important to note that while many of the details of how such factories should be partitioned, and various materials processing technologies were explored in detail in those studies (see Fig 3) the robotics, control and manufacturing components of these systems were little more than the sketches shown in Fig 4. A forthcoming book reviews the history of these and other efforts to

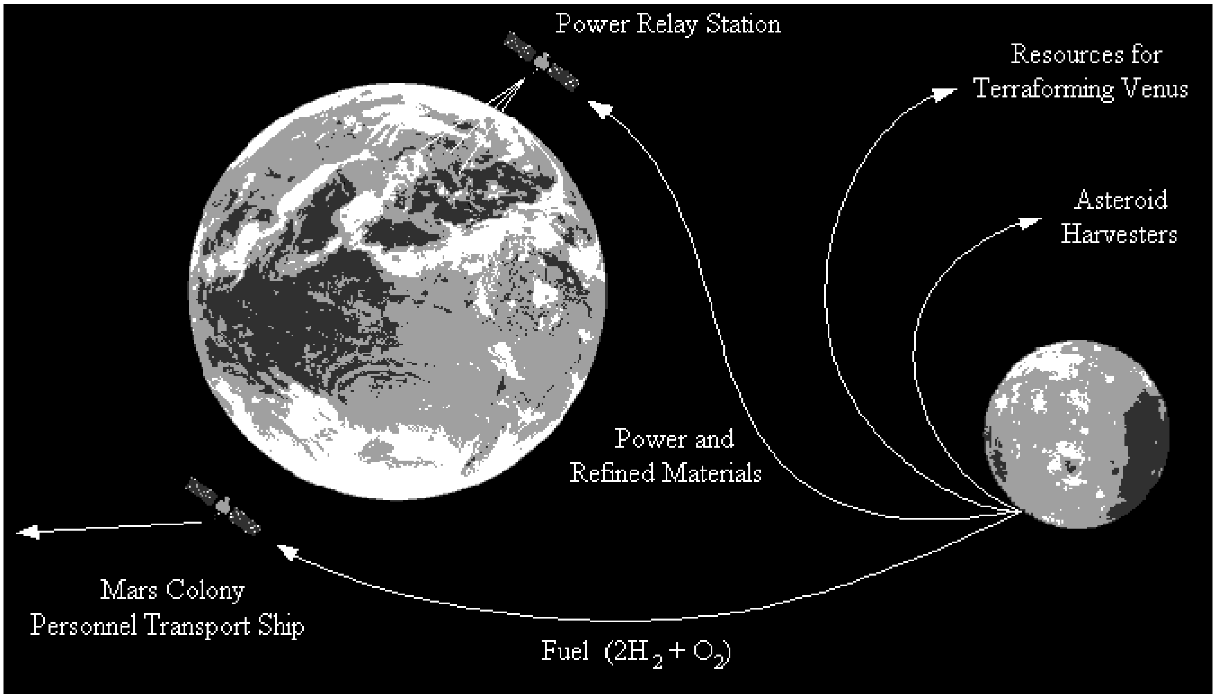


Figure 2: The Impact of Self-Replicating Lunar Factories on the Utilization of Space

understand self-replicating systems over the past fifty years [46]. That book represents the most comprehensive review to date on the subject of self-replicating systems, and is an excellent reference book. It will be clear to anyone who has read that book that the goals of this Phase I work are clearly distinct from what has been accomplished by others in the past.

It is important to note that no deterministic self-replicating mechanical/robotic system had ever actually been built prior to our work, and to do so was one of the revolutionary goals of this Phase I effort. In addition, novel minimalistic materials and power generation technologies that we developed and incorporated into our Phase I architecture makes it dramatically different than those that have come before. Our vision is illustrated in Figures 6 and 7.

1.1 Impact on the Exploration and Colonization of Space

Space is a potentially limitless source of materials and energy that is available for mankind's use. And the integration of both manned and robotic missions to the moon and Mars as part of President George W. Bush's initiative recognizes this fact as well as the fundamental problems associated with launching massive amounts of material from Earth into outer space. Therefore, strategies for in-situ resource

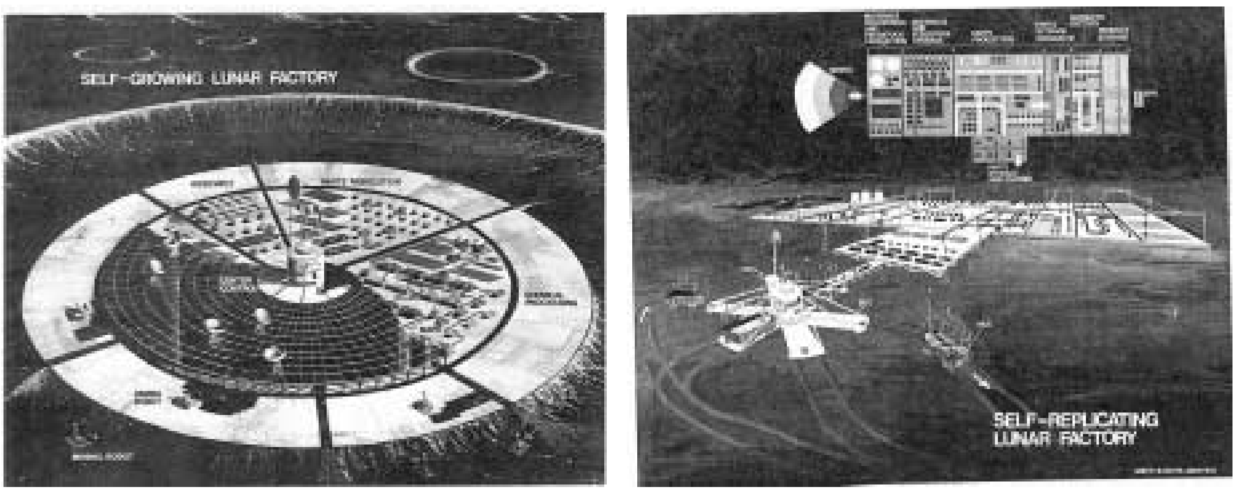


Figure 3: Self-Replicating Lunar Factory Concepts circa 1980 [43, 140]. (Reprinted with permission from R. Freitas)

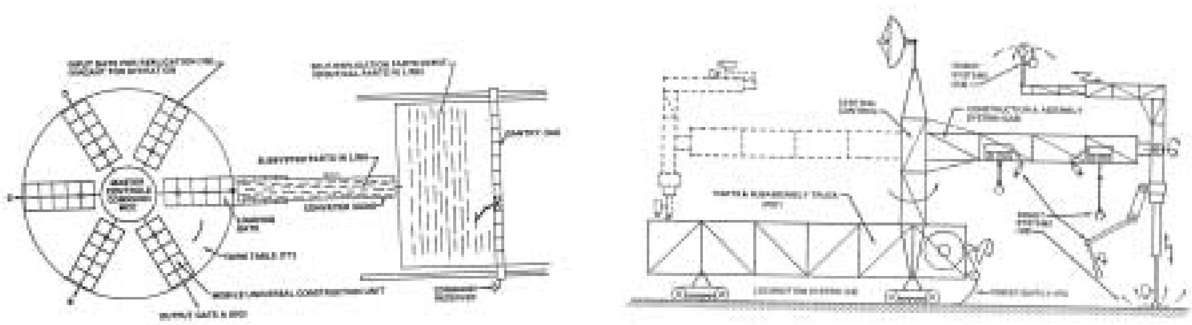


Figure 4: Conceptual Universal Constructor circa 1980 [43, 140] (Reprinted with permission from R. Freitas)

utilization must be given serious thought. This is summarized by the quote:

"If god had wanted man to explore space he would have given us a moon." Dr. Kraft Ehricke (circa 1980)

The development of lunar resources over the period 2015-2045 has the potential to greatly enhance man's ability to explore and colonize space. 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 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 spares the Earth's atmosphere from the pollution resulting 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 metric tons of ice trapped in the south polar region of the moon [42]. 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 [121]. Other technologies for materials processing that do not depend on the existence of water (such as electrolysis of molten salts) could also be used. The simplest such strategy would be to separate the metallic iron crystals embedded in the gains of regolith (see Figure 5) by grinding and applying strong magnetic fields.

Alternative propulsion technologies for deep-space probes such as ion engines based on the inert gases known to be trapped in the lunar soil could be developed in place of the $2H_2 + 0_2 \rightarrow 2H_20$ paradigm. Hence the impact of our concept does not depend on the existence of large amounts of lunar ice, but its implementation would be made easier.

Equipped with refined materials and propellent derived from the moon, cultivation of other space resources will be made much easier. One natural candidate would be to force asteroids rich in nickel and iron from the asteroid belt into lunar orbit using rockets constructed on the moon and shot to the asteroid belt. Using massive

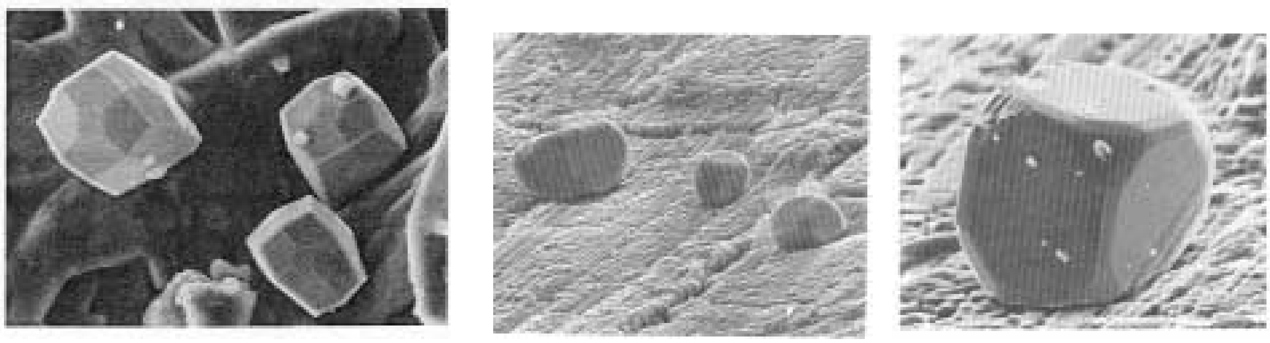


Figure 5: Microscopic Crystals of Metallic Iron in Samples Returned from Apollo Missions (Reprinted with permission from Dr. John Lindsay [83])

electromagnetic launchers to propel these "asteroid harvesters" from the moon along gravitationally favorable paths would conserve fuel for the harvesters to bring the asteroids back. Another candidate would be to drive materials from the moon along a path to rendezvous with Venus. Then a massive satellite network could be constructed around Venus to block the sun's energy in order to reverse the greenhouse effect there and begin the process of terra forming. Other materials derived from the lunar regolith could be sent to this satellite network and injected into the Venusian atmosphere to neutralize the sulfuric acid in the clouds. Of course, such ideas are highly speculative, and are not the subject of this Phase I study, though they do serve as long-term (100-year) goals which would be facilitated by our architecture.

1.2 Impact on the Development of Industries in Earth Orbit

Low-Earth orbit (LEO) has the potential to serve not only as a staging area for missions to outer space, but also as a microgravity environment for industrial production of new metal alloys and biomedical products. In fact, one initial driving force for the establishment of the current space station was exactly these kinds of applications. Having facilities on the moon that can send materials and energy (either in the form of H_2 and O_2 or as a concentrated beam of electromagnetic radiation) to LEO facilities will dramatically increase the size and output of the LEO facilities. In addition, whereas re-entry into the Earth's atmosphere from outer space is a relatively clean process, the launch of rockets using solid fuels into space creates toxic byproducts which cannot be tolerated by the environment on a massive scale. Hence, self-replicating production facilities on the moon will provide a way to ob-

tain LEO production facilities without the cost and negative environmental effects of establishing the same facilities with massive amounts of material sent from Earth.

In addition, having the ability to send massive amounts of materials to LEO opens up the possibility of producing a thin shield to limit (by perhaps fractions of a percent) the amount of solar energy entering the Earth's atmosphere. While the design and implementation of such a shield is not the subject of this work, and such a system would have to be designed to allow the Earth itself to radiate energy out to space, one cannot even imagine such a system being possible without the energy and refined materials that the architecture in this work seeks to exploit.

2 Concept Description and Objectives

We envision that a fully functional lunar factory site will occupy approximately one square kilometer. However, the precursor that is launched from the earth will be a minimalist system consisting only of two robots, a small furnace, molds, mirrors and solar panels and weighing between five and ten metric tons. Our concept of the full self-replicating robotic factory (which will be constructed under remote control from the earth using the precursor system) consists of the subsystems which are described below.

1. *Multi-Functional Robots.* These are robots capable of assembling copies of themselves given a 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.

2. *Materials Refining and Parts Manufacturing 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 make parts. A long-term (30-40-year) goal would be to develop the capability to separate the oxygen from the silicon, aluminum, and iron oxides that are plentiful in the regolith. In the shorter term (10-20 years), metallic iron extracted magnetically from the regolith and the

remaining glass will serve as the sole construction materials. 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.* Four types of solar energy production are being considered for use in this concept: (1) photovoltaic cells; (2) solar radiation that is reflected and concentrated with mirrors; (3) thermoelectric generation based on temperature gradients; (4) radiometer-based solar windmills. Photovoltaic cells would power the robots, electromagnetic launch system (see below), and electrolytic separation of elemental metals from oxides in the materials processing plant. 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 will 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, three 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. A third alternative is to store kinetic energy mechanically in flywheels.

4. *Electromagnetic Launch Systems.* These would be used for long-distance transportation (e.g., for sending materials to low-Earth orbit, 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 until it lands at its new location. If the scale is made large enough, the same guns could shoot materials directly to low-Earth orbit. If this is not feasible, the guns could at least serve as a loading device for tether transport systems that have been studied by others under previous NIAC support (see Section 4).

   Since an electromagnetic launch system consists of many repeated identical units, and since the gun's role does not occur during the replication process,

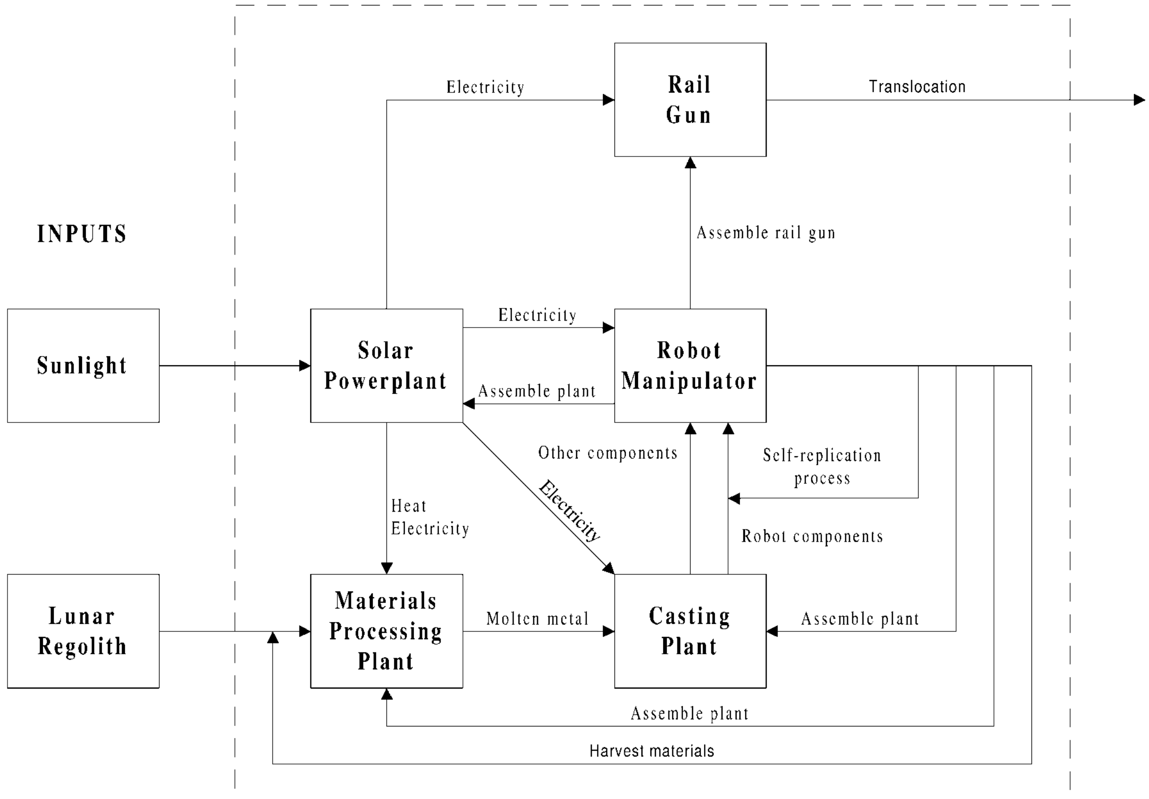


Figure 6: An Architecture for Self-Replication. Here 'rail gun' can be one of any number of electromagnetic launch technologies, and 'casting' is one of a number of parts manufacturing technologies

there is no need to send a whole electromagnetic launch system 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 electromagnetic launch system.

Our specific architecture that proposes to integrate these constituent systems is described in Figure 6. 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 Figure 6. Here the "robot manipulator" is what is known as a *mobile manipulator* in the robotics community [49, 90, 34, 66]. It is a mobile robot with attached manipulator devices such as arms and/or grippers. It is not just a fixed manipulator arm.

Items (2)-(4) listed above have been studied to various degrees elsewhere. We examined how these results can be synthesized from a systems-engineering perspective,

but our main focus was (1). In particular, in this Phase-I NIAC effort we sought to do the following:

- Evaluate existing materials processing technologies that can be used in the lunar environment, and rate each according to how well they can be used to produce the materials required for subsystems (1)-(4) above. These include electrolytic deoxygenation of molten regolith, and chemical processing.

- Calculate the physical characteristics required for each of the subsystems (1)-(4) in order for the concept to work. Namely, determine how massive must the electromagnetic launch system be, and what will its power consumption be ? What surface area must be covered with photovoltaic cells manufactured in situ in order to provide power for the electromagnetic launch system, robots, and materials processing unit ? Power *generation* is one issue, but how can energy *storage* take place ? Compare modalities assuming sub-regolith ice vs. no H_20. Examine the potential of running an operation without power storage (e.g., by only using electricity generated at any given time). Perform a careful counting of system mass, and investigated methods to transport our system to the moon.

- Determine what minimal intelligence and sensing is required for robotic systems to autonomously self-replicate. While very interesting work has been performed in the past on robotic systems with minimal sensing in highly structured industrial settings [39, 14], and robots that exhibit complex undirected behaviors have been constructed from simple components [12, 57], minimal intelligence robots that demonstrate repeatable, deterministic, directed behaviors in unstructured environments have yet to be demonstrated. In addition, no previous work has directly addressed the manufacture of simple computing and sensing elements without the availability of conventional terrestrial factories. Questions to be answered include: Does one need a microprocessor, or can reliable and repeatable complex behaviors be obtained using discrete transistors, resistors, capacitors, inductors and photodiodes ? Is analog or digital better in this context ? Can crude electronic components be manufactured in situ using simple manufacturing processes ?

- Determine a strategy for the optimal diffusion of self-replicating factories on the moon, and perform a mathematical/computational analysis of this diffusion

process. That is, at what distribution of distances should an electromagnetic launch system shoot replicas, and at what orientations relative to the previous electromagnetic launch system should new electromagnetic launch systems be built ? The PI has written a number of applied mathematics papers on modeling physical phenomena as diffusion processes on group manifolds, and these tools can be brought to bear on the current problem.

- Build 'toy' (prototype) robots out of modular components (including a microprocessor) and show that it is able to autonomously assemble replicas of itself without human intervention. This was a key milestone to be achievable in order for autonomous self-replication to be feasible.

- Design and implement simple circuitry that can be used in place of the microprocessor in the goal stated above, and demonstrate how such circuits can be assembled by robots which are controlled by the same kind of circuit.

- Integrate (rather than duplicate) relevant technologies developed in other NIAC projects. See Section 4 for examples.

An example of what one factory replica might look like is shown in Figure 7. The scenario depicted here was constructed during Phase I. During Phase II, we will seek to implement a full self-replicating factory which takes in plastic pellets and basic metal parts and produces a functional copy of itself.

3 Advanced Concept Development Work Plan

During this six-month NIAC Phase I effort, we proposed to accomplish the following goals during the time periods indicated below:

Months 1-2: Evaluate the state of the art in materials processing, electromagnetic launch technology, microwave power transmission, knowledge of lunar resources, and solar power technologies. Perform a regression analysis to extrapolated the anticipated state of these technologies in the 2020-2040 time period based on the rate of their development over the past 50 years.

Months 3-4: Devise simple circuits for non-microprocessor-based intelligent machines that would be plausible to manufacture using current technologies and lunar

Figure 7: Close-Up View of Our Self-Replicating Lunar Factory Concept

resources. Perform analysis of diffusion of proliferating self-replicating robots on the lunar surface.

Months 5-6: Complete autonomous robot prototypes to demonstrate feasibility of mechanical aspects of the self-replication process. Write phase I report.

All of these milestones were met, though the amount of time required for writing this final report extended one month past the six months of the grant. Also, we note that the regression analysis is no longer appropriate due to the change in US space policy articulated by President George W. Bush on January 14, 2004. Therefore this analysis is not included in this report.

If this phase I award is followed by a phase II, our effort at that time will focus on the development of second-generation robot prototypes and prototypes of each of the constituent systems on a much smaller length scale than the actual systems and implement a scale model of a functional self-replicating lunar factory. We will use materials that simulate those that would occur on the lunar surface in a way that is reasonable in a university lab setting. For instance, instead of actually melting

sand by concentrating the sun's rays, we will use plastic or wax pellets as a proxy for the lunar sand. Instead of actually manufacturing solar cells or electromagnetic launchers, we will defer to others who are currently working on such things, and construct functional scale models that are appropriate proxies for such subsystems.

4 Integration of Complementary Work Funded by NIAC into our Architecture

As stated in Section 1, the idea of self-replicating systems has been pondered for more than 50 years, and there was significant interest within NASA in pursuing such systems 25 years ago for lunar development, though the idea has not been pursued to any serious degree in the scientific/technical literature since that time.[1] *However, prior to our Phase I study, no concrete system or architecture for active fully self-replicating robots had ever emerged. And determining the feasibility of such systems and implementing functioning prototypes of certain subsystems were the main goals of this work. These objectives were met successfully and the details are described in subsequent sections of this report.* But first, the relationship between this work and work proposed by others (both under NIAC funding and other sources) is reviewed.

An important part of our architecture for self-replicating robotic factories is the integration of other architectures and technologies that are extremely promising, but are still not in a mature state. In this section we review some of the architectures and technologies that have recently been funded by NIAC, and explain how these can be integrated into our concept.

As has been mentioned previously in this report, the issue of access to water greatly alters the kinds of materials processing and energy storage technologies that might be used. In essence, while one can circumvent the absence of water and use other technologies, if sufficient quantities of water can be harvested from the moon, then everything becomes easier. In a recent NIAC phase I study, Rice investigated an architecture for recovering lunar ice [116]. In a recent NIAC student study, Mr. Darin Ragozzine of Harvard University examined biomining processes for extraction of lunar metals [117]. We can adapt the results of these studies and examine how

[1]That is not to say that the concept should not be pursued further. In fact, many concepts including travel to the moon, electromagnetic launch systems, solar sails, space elevators, and lunar bases originated in the science fiction literature and required substantial technical concept development before their feasibility could be determined.

best to modify them to fit within the context of our architecture for self-replicating systems in Phase II.

Another issue is the energy required for transporting from low-Earth-orbit to the lunar surface and vice versa. This is important for the transportation of the initial seed factory to the moon, and the transportation of refined materials from the moon back to low-Earth orbit. In a recent phase I/phase II NIAC study by Hoyt, the energetic requirements of tether transport systems were investigated [61]. If such systems were implemented, this could dramatically reduce the energy and size requirements of the electromagnetic guns in our architecture. This is because the guns would only serve as the loading device for the tether transport system, rather than as a means for providing the energy for the whole trip to low-Earth orbit. Of course, if tether transport were to be integrated into our concept, the mass traveling back and forth would need to be balanced for angular momentum to be conserved without additional energy input. Another alternative for the transportation of materials between the Earth and moon would be the space elevator developed under NIAC funding by Bradly Edwards. We will investigate in phase II the modification of our architecture to incorporate both earth-based and moon-based space elevators for the transportation of materials and resources back and forth.

A third important architecture that could be integrated into ours for the concept of self-replicating robots to succeed is that of in situ production of photovoltaic solar cells. This has been studied recently by Ignatiev and coworkers in a NIAC Phase I study [62, 37]. In phase I we examined alternative power production technologies such as radiometers and Sterling engines. The benefit of these "photo-mechanical" energy production technologies over their "photo-electric" competitors is that kinetic energy can be stored directly in flywheels and converted to electrical current via generators when needed. This circumvents the need for batteries, which may be difficult to manufacture in situ if water is less abundant than anticipated.

As the last example of a complementary set of technologies, Lipson [84] studied fabrication technologies based on rapid prototyping techniques whereby plastic parts are created by machines for assembly of new machines. This can be viewed as an important technology for the component-producing subsystem in our proposed architecture, but it in no way overlaps with our proposed objective of demonstrating fully autonomous electromechanical self-replication from a set of basic components. Both ideas from rapid prototyping such as 3D printing or more traditional manufac-

turing techniques such as casting were considered during our Phase I. The benefit of 3D printing is the versatility and variety of shapes and devices that can be printed. The drawback is that it is difficult to imagine making this technology self-replicating using an architecture of reasonable size and weight. We have therefore concentrated on technologies which are easy to "bootstrap" requiring very little to be launched. We also take the next step of examining the manufacture of other crude electronic and electromechanical components from lunar resources without the presence of a conventional factory.

The PI and a subset of his current students have been working on the concept of self-replicating robotic systems for two-and-a-half years. We have developed models of systems that demonstrate "directed replication" under remote control from a human user, as well as systems which autonomously perform certain subtasks in the self-replication process. This has resulted in three publications [18, 20, 132]. Our already high rate of progress in this area (which was achieved during the first two of those years without funding) was significantly accelerated with Phase I funding from NIAC. In the six-month period of the Phase I award, the PI's group produced three additional manuscripts which have been submitted for publication, and have been included in the appendices to this report.

5 Composition of the Moon: Resources Worth Developing

For self-replicating lunar factories to be useful, the material inputs must be available for the systems to self-replicate and spin off refined products such as solar panels and construction materials to be sent to LEO or elsewhere. Therefore, as part of Phase I, some effort was taken to survey the literature on lunar materials processing.

The most abundant elements in the lunar regolith (as a Percentage of the Total

Number of Atoms) are [121, 135]:

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
Aluminium	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 [55, 58, 121]:

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.

In addition to oxides of aluminum, (alumina - Al_2O_3), silicon (silica - SiO_2), calcium (CaO) and iron, minerals such as calcic plagioclase feldspar (anorthite, $CaAl_2Si_2O_8$, containing dissolved $NaAlSi_3O_8$), pyroxene (solid solution of $MgSiO_3$ and $FeSiO_3$) with various levels of dissolved $CaSiO_3$, olivine (solid solution of Mg_2SiO_4 and Fe_2SiO_4), and ilmenite ($FeTiO_3$) have been discovered in returned lunar samples. Other minerals such as chromite, $FeCr_2O_4$, and $Ca_3(PO_4)_2$ and $Ca_5(PO_4)_3F$ have also been found in very small concentrations.

Various chemical methods have been proposed assuming the use of H_2, F_2 or Cl_2. However, the most commonly proposed methods for extracting metals from the lunar regolith are electrolysis and pyrolysis. In electrolysis, a current is applied through electrodes placed in molten mineral salts. Metals form at one electrode and oxygen bubbles at the other. In pyrolysis, the salts are vaporized, and the resulting

gases are either directed electromagnetically or allowed to passively condense. Two alternatives are simply to use the glass resulting from melting the lunar regolith as a construction material, and to use electromagnetic or electrostatic separation methods before melting the materials. In this way, any naturally occuring magnetic minerals or alloys can be recovered in advance. The use of alternating electromagnetic fields to induce magnetic fields in nonferrous conductors is also possible to separate out any metallic aluminum or copper.

Many promising materials processing technologies have been investigated [10, 35, 119, 7, 26, 51, 69, 91, 102, 136, 133, 27, 122, 150, 118, 141, 33, 108]. Some of these require the use of water and others use microwaves, electrolysis or pyrolysis. In short, it appears that many researchers over the years have worked on materials processing technologies for harvesting lunar resources. Therefore, in the context of a Phase I NIAC award, it is sufficient to simply make a record of these prior works and develop an understanding of their relative merits in the context of an overall architecture for self-replicating lunar factories.

A low-energy method for extracting metals from the lunar regolith is by use of an electromagnet. When used in DC-mode, this attracts iron, nickel and cobalt which can be used to make cores for new electromagnets. When used in AC mode, this induces currents in nonferrous metals. The resulting induced magnetic field can be used (it the electromagnet is designed properly) to attract or repel nonferrous metals as in Figure 8. In addition to this minimalist approach to materials separation, an alternative technology based on spinning permanent magnets to induce fields in nonferrous conductors was constructed during Phase I to assess feasibility. While this should work in principle, our prototype did not demonstrate the desired materials separation. We believe that this is because the rotation speeds were not high enough. This potential alternative to AC Electromagnets for the attraction/repulsion of nonferrous conducting materials is shown in Figure 9.

Figures 10 and 11 depict conceptual and hardware implementations of a prototype materials separation system for extracting ferrous materials.

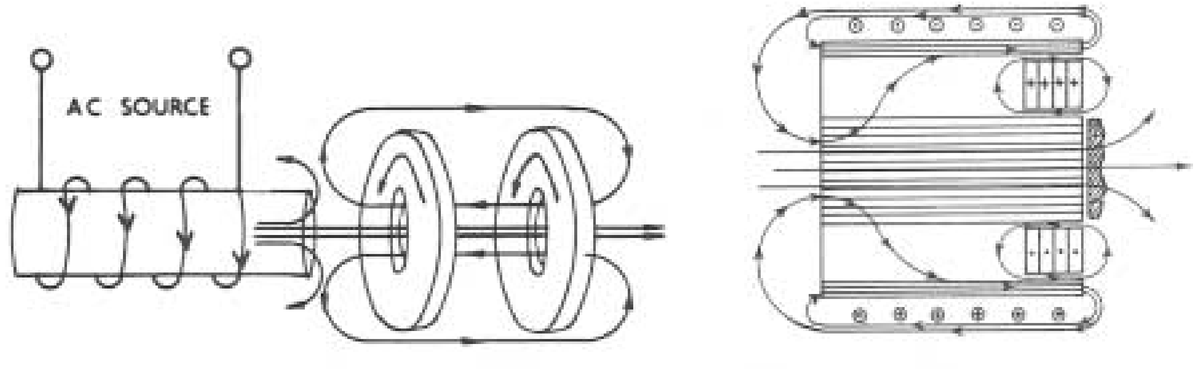


Figure 8: AC Electromagnets for Attraction of Nonferrous Conducting Materials (Reprinted with permission from [32])

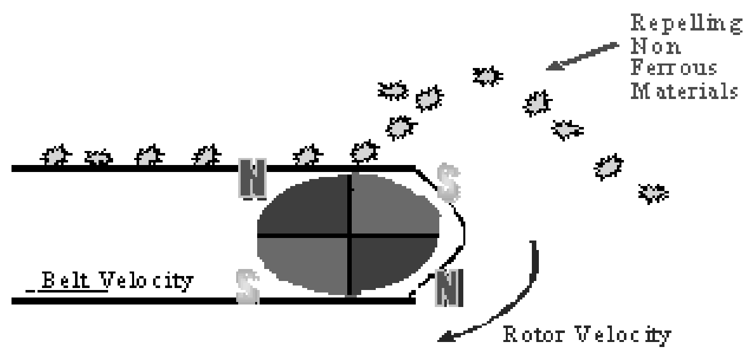


Figure 9: Repulsion of Nonferrous Conductors Using Rapidly Rotating Permanent Magnets

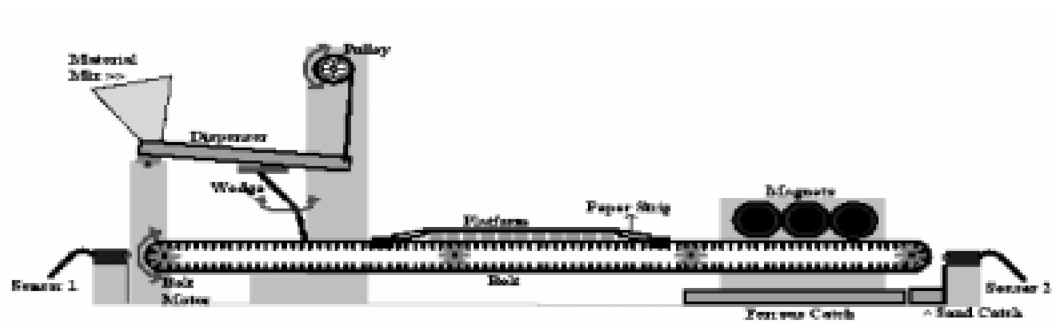


Figure 10: A Conceptual Magnetic Materials Separator

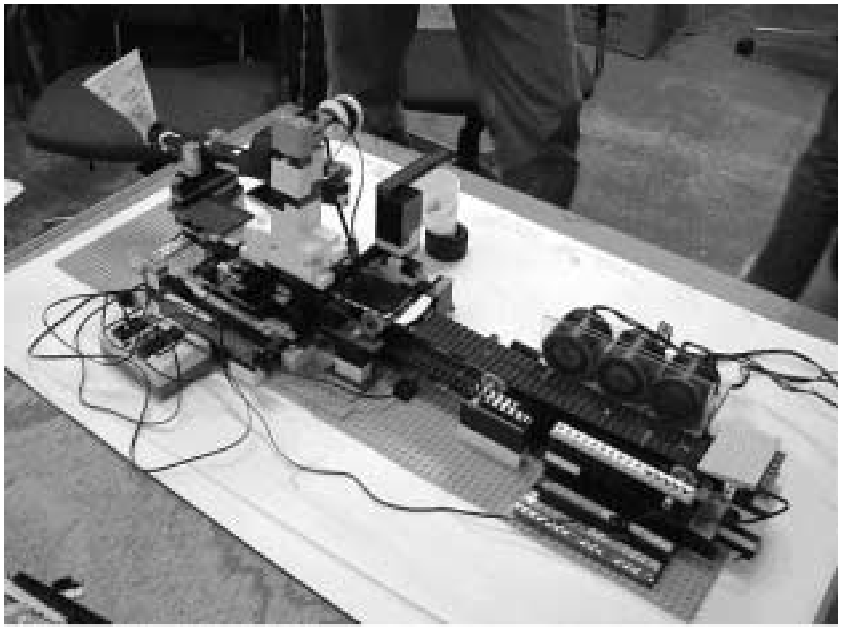


Figure 11: Student Implementation of a Magnetic Materials Separator

6 Classification, Design and Implementation of Self-Replicating Robots

Before we begin investigating design criteria for physical implementations of 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 robot reproduced, and in what environment ? This issue goes back to von Neumann himself [129], 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 this NIAC Study, the goal was 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 required 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.

6.1 Categories of Self-Replicating Systems

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 12 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".

We classify directly self-replicating robots into four groups according to the char-

acteristics of their self-replication processes. The following are explanations of each directly self-replicating robot group.

Fixture-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.

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.

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.

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.

The primary characteristic of *indirectly replicating robots* is that the original robot or group of robots work together to build a robot-producing factory or some type of

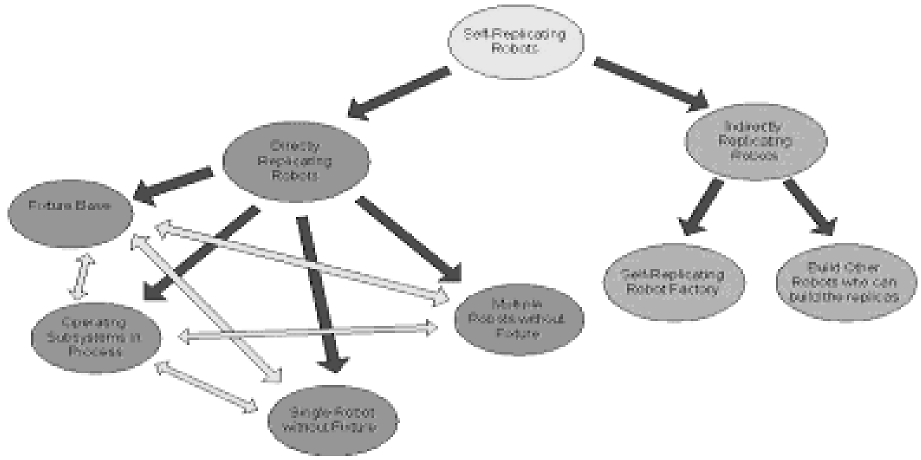


Figure 12: Catagorization of Self-Replicating Robotic Systems

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.

6.2 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:

- The robot must have the ability to independently locomote on a 2-D surface that deviates from an ideal plane;
- The robot should have adaptable rigid fixtures for each task;
- The actuators of the robot must consist of rigid subunits, each of which can be assembled by simple motions;
- The robot 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 its payload to a height above that plane.
- The overall design must be compact and light weight in order for it to be feasible for the initial system to transport 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.

Figure 13 illustrates a first attempt at a self-replicating robot which functions under remote control. This system (which was designed by the PI's students) demonstrates that it is in fact possible from a mechanical perspective for a robot to assemble subsystems to form an exact functional copy of itself under remote control. Such a paradigm may be the first logical step in self-replicating lunar robots.

The robot in Figure 13 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. The replication 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.

We also designed and implemented the fully autonomous self-replicating robot in the context of a highly structured environment shown in Figure 14. Videos of both systems can be found on the PI's webpage.

6.3 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

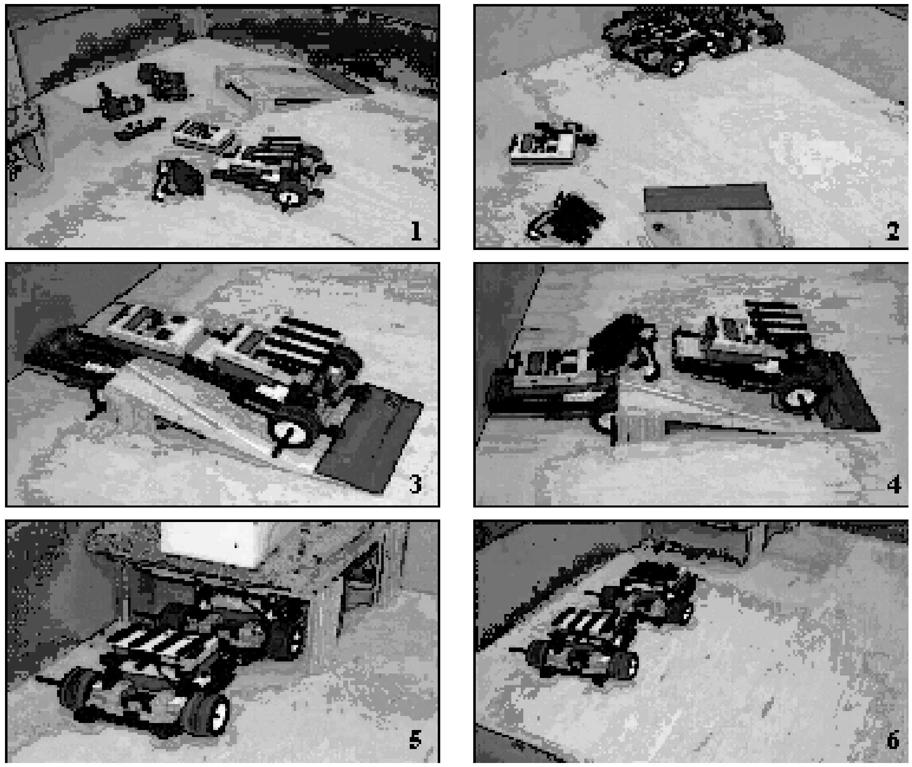


Figure 13: A LEGO Robot Capable of Assembling an Exact Replica Under Remote Control (Designed by the PI's Students)

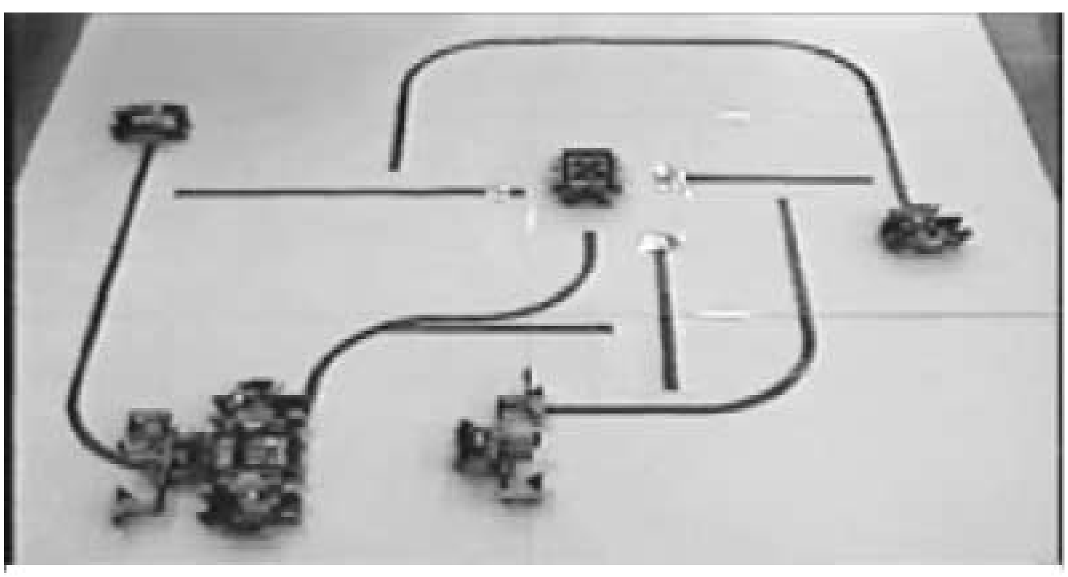


Figure 14: A LEGO Robot Capable of Autonomously Assembling an Exact Replica in a Highly Structured Environment (Designed by the PI's Students)

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 difficulties, 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 PI extensively in previous work on high-degree-of-freedom manipulators.

Figure 15 shows a castable shape which is a cross-section of a solid annulus with a helical hole. When objects of these formed from insulating material and are stacked, the result is a cylindrical center hole straddled by a helical hole. We constructed a prototype using this idea, and filled the center hole with a steel bolt, and the surrounding helix was filled with a slurry of iron filings and salt water. The result was the functional electromagnet shown in Figure 16. This illustrates the feasibility of constructing electromagnets in situ. In that context, both the coil and core could be formed from molten iron, and the castings which form the housing could be made of the insulating oxides in the lunar regolith.

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 section). 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.

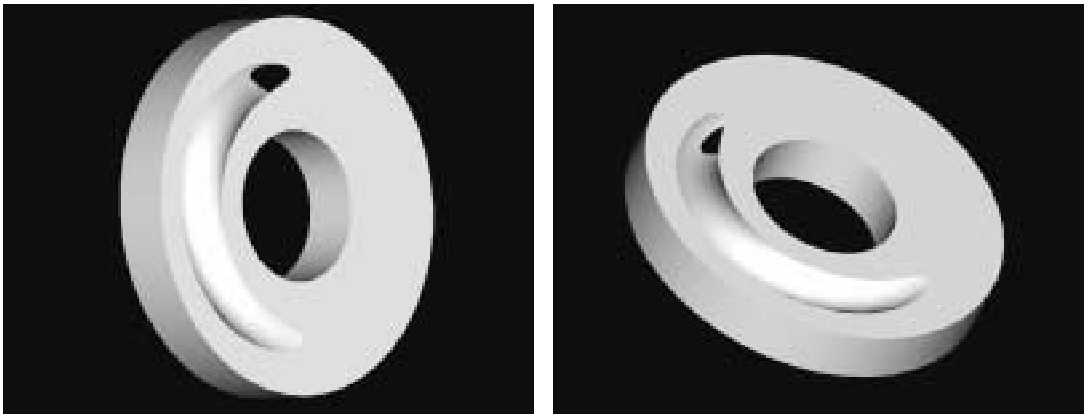


Figure 15: A Castable Shape for In-Situ Manufacturing of Coils

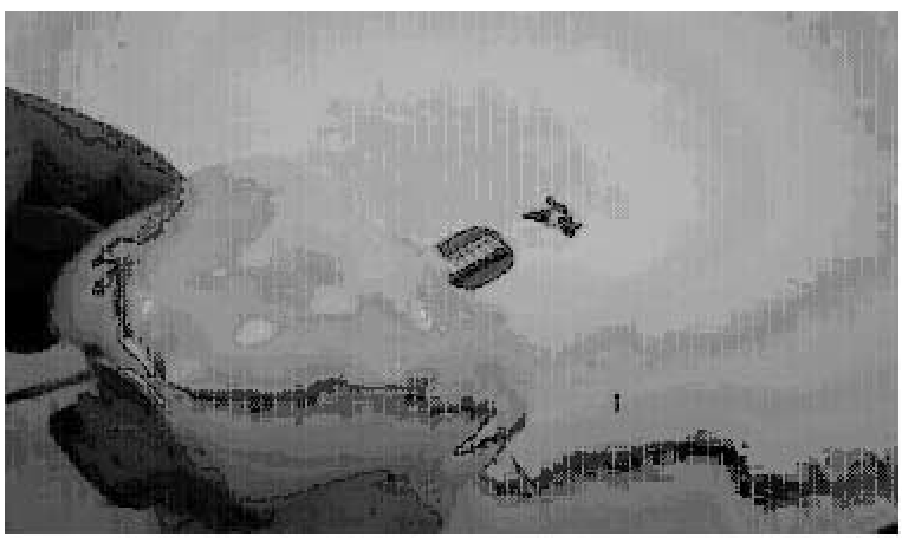


Figure 16: A Functional Electromagnet Constructed by Stacking and Filling the Shapes in Figure 15

7 Mass Requirements for Initial Bootstrap

In this subsection the mass of a modest (6000 kg) initial system consisting of two robots, a small furnace for materials processing, and 100 square meters of solar panels to power the system are estimated. To some extent these mass specifications are arbitrary, since the system which is initially launched can be scaled up or down in size depending on the available launch capabilities. The only difference will be in the amount of time that it takes the initial system to process materials and manufacture components for construction of the full systems described in the architecture studied in this report.

Mass of Robots

The mass of each robot in the initial seed system is estimated at 500 kg for a size of 2 meters by 1.5 meters and 1 meter high. This is in contrast to the Soviet Lunokhod-1 robotic rover [65] which had dimensions of 2.2 by 2.2 meters and had a mass of 756 kg, and the American lunar rover which had dimensions 3.1 meters by 1.83 meters and height of 1.14 meters and a mass of 218 kg [28]. The robot chassis (with a mass of 250 kg consisting of batteries, structural support, communications hardware, and drive system) will be equipped with the following additional items: 10 square meters solar arrays (mass estimated at 25 kg) two arms for manipulation (25 kg each), an actuated bulldozer shovel (125 kg) for scooping regolith, a grinder/electromagnetic materials separator (25 kg) and cameras, computers, power electronics and control hardware (25 kg). In addition to the mass for the two functional robots, a full set of mechanical components for a third robot will be included which can be used to make molds for replicas. This brings the total mass of the robots in the system to 1500 kg.

Energy Production Components

External to the robots will be additional energy production equipment which will be too bulky to be mounted on mobile platforms. This will include an additional 10 copies of 100-square-meter solar arrays (10 x 250 kg). Only one of these arrays will be required for the initial seed factory, and the others will allow for the initial expansion of the system by a factor of 10. After that point, construction of alternative power production facilities using in-situ resources will begin.

Electromagnetic Launcher

An electromagnetic launcher for transporting thousands of kilograms of material into lunar orbit would itself be extremely massive (e.g. hundreds of thousands of tons). For the initial seed factory, only sample components to be used in the construction of such a launch system would be included. Sand casting based on these initial components can be constructed. Light-weight geometrically correct proxies of the sample components (which would be repeated many hundreds or thousands of times to construct the whole launch system) are expected to have a total mass of 1000 kg.

Materials Processing

The furnace is expected to be relatively small. It will have a mass of less than 1000 kg, and will have the ability to melt several kilograms of iron or glass each hour. It will be an electric furnace similar to 'Li'l Bertha' [52] (see Figure 17), though it will be larger and powered by solar panels. The fact that a furnace like Li'l Bertha can be constructed from low-tech materials, many of which are constructed by hand, makes the in-situ replication of such furnaces a promising possibility.

Once the initial bootstrap process is complete, alternative technologies such as direct concentration of solar energy with massive mirrors also will be possible.

8 In-Situ Energy Requirements and Means of Production and Storage

8.1 Energy Production Technologies

A number of technologies can be used to generate solar energy using in-situ lunar resources. These various technologies are compared and contrasted in this section.

One natural choice is the use of photovoltaic cells. As discussed elsewhere in this report, this has been investigated by others under NIAC funding. The benefit of this technology is that there is plentiful silicon on the lunar surface. The drawback is that the purification process requires large amounts of water and other chemical processing that may be difficult to attain in all but the lunar south polar region.

Sterling engines are a thermo-mechanical means for generating kinetic energy from a heat gradient (see e.g., [123]). Such heat gradients exist between the lunar surface and a depth of several meters under the surface, as well as surface regions composed of different color materials. The benefit of Sterling engines is that the parts can be produced by a combination of casting and machining processes, which are relatively

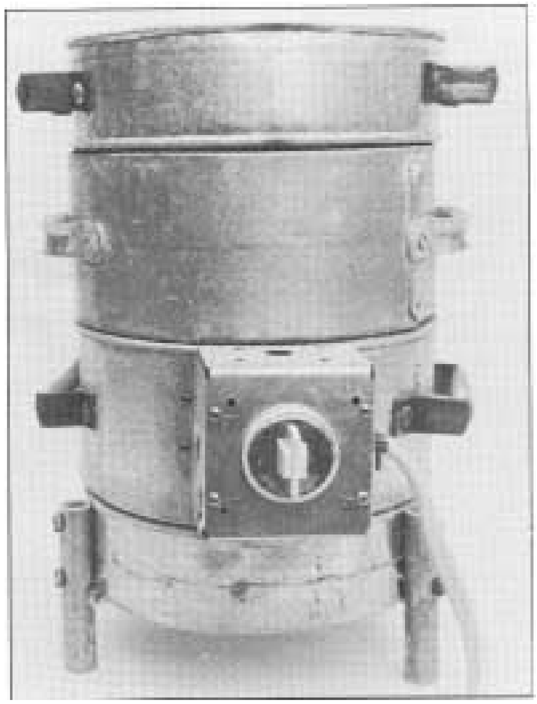


Figure 17: Li'L Bertha: A Simple Electric Furnace Capable of Melting Aluminum at Home [52] (Reprinted with permission from Lindsay Publications

robust and reproducible using in-situ resources. The drawback is that Sterling engines require a working fluid which would be lost over time unless very tight seals are maintained.

A technology which converts photon momentum gradients directly into kinetic energy is the radiometer. The benefit of radiometers is that they require no precision machining, can be constructed from in-situ resources by casting, and require no working fluids. The operating principle is that large surfaces are covered with absorbing and reflecting colors on opposite sides. These are arranged symmetrically at ninety degree increments around a common fulcrum. As light impinges on the radiometer, the difference in reflectivity of opposing sides causes a net torque around the fulcrum. Essentially a radiometer is a rotational solar sail or solar windmill. The drawback with this technology is the enormous size that would be required to generate significant amounts of energy, and the possible interference of even the minute lunar atmosphere.

Once energy is harvested, storage becomes a concern. In the presence of abundant water, energy storage can easily be attained by the electrolysis of water and the

separate storage of hydrogen and oxygen. This would be a natural choice if electrical energy generated from photovoltaic cells were to be stored directly. Likewise, electrical energy obtained by a generator attached to a Sterling engine or radiometer could be stored in this way. However, if water is scarce, other technologies need to be investigated. An alternative would be to perform electrolysis on molten regolith to separate the metals from the oxygen, and then run the process in reverse by burning/oxidizing the metals to produce power. This oxidization of molten metal would require power to maintain the metals in a molten state, and the energy losses due to conductive heat transfer to the surroundings and radiative heat transfer to space may be significant. In effect, this technology could serve as an inefficient battery technology.

An alternative to batteries which discharge electrical current as a result of chemical reactions, one can imagine capacitor banks that hold a generated current and simply discharge over time. The problem is that traditional capacitors rely heavily on organic materials to serve as the dielectric material. While it is plausible that the lunar minerals may be used to form insulating glasses, it is not clear how much charge could be stored in capacitors made from such glasses. And it is not at all clear whether or not such capacitors would withstand the mechanical stresses associated with holding high charge densities.

A natural choice in both the context of a Sterling engine and radiometer which does not have the drawbacks of batteries and capacitors is the flywheel. A flywheel stores energy in the form of rotational kinetic energy. It can be constructed from casting lunar materials into molds, and the only required precision parts are the low-friction bearings on which the flywheel spins. As energy needs to be recovered from the flywheel, it can drive an electrical generator to produce electricity. In the case of a radiometer, energy production and storage take place in the same unit, and electricity is siphoned off using a generator in a continuous fashion.

The energy produced in situ will be used to power each of the subsystems in the architecture developed during this phase I study. For a modest initial system consisting of two robots, a grinder/electromagnetic materials separator and a small furnace for materials processing, the required power may be as little as 10 kilowatts. This assumes that each robot runs on 2 kilowatts (which is far more than what is required by full-scale robots designed and operated in the PI's lab which have a mass of 100 kilograms), the furnace runs on 4 kilowatts (which is enough to melt several

pounds of aluminum, iron or glass every hour [52]), and another 2 kilowatts are used for grinding and electromagnetic separation. This total amount of power is equivalent to the average solar energy which falls on 10 square meters of the lunar surface. An energy production technology which operates at 10 percent efficiency would therefore require a 100 square-meter (10-by-10 meter) area. This is very modest, and would scale well as the system reproduces.

The most energetically costly element in our architecture is the electromagnetic launch system. The power requirements of such systems have been analyzed by Northrup [99], O'Neill [101, 3, 4, 5] and Clarke [24]. This element of the total system architecture need not begin to utilize energy until the solar energy production facilties are multiplied many times over. When the exponential growth of self-replicating systems is observed, the energy requirements computed by Northrup, O'Neill and Clarke will become feasible in linear time. The calculations that justify this are discussed in the following subsection.

8.2 Analysis of Energetic Requirements for Launching Materials into Lunar Orbit

In this section, computations are performed to analyze the energy required to launch materials from the surface of the moon into low lunar orbit.

Let r_0 denote the lunar radius, and let $\mu_l = GM_l$ denote the product of the universal gravitational constant and the lunar mass. Consider a device which launches a payload of mass m_p at an angle of elevation ϕ_0 relative to the lunar horizon with initial speed of v_0. The position of the projectile at time t in the orbital plane relative to a frame of reference fixed at the center of the moon is denoted as

$$\vec{x}(t) = \begin{pmatrix} r(t)\cos\theta(t) \\ r(t)\sin\theta(t) \end{pmatrix}.$$

The velocity of the projectile is therefore the time derivative of this absolute position:

$$\vec{v} = \dot{\vec{x}} = \begin{pmatrix} \dot{r}\cos\theta - r\dot{\theta}\sin\theta \\ \dot{r}\sin\theta + r\dot{\theta}\cos\theta \end{pmatrix}.$$

kinetic energy of the projectile is

$$T = \frac{1}{2}m_p(\dot{r}^2 + r^2\dot{\theta}^2).$$

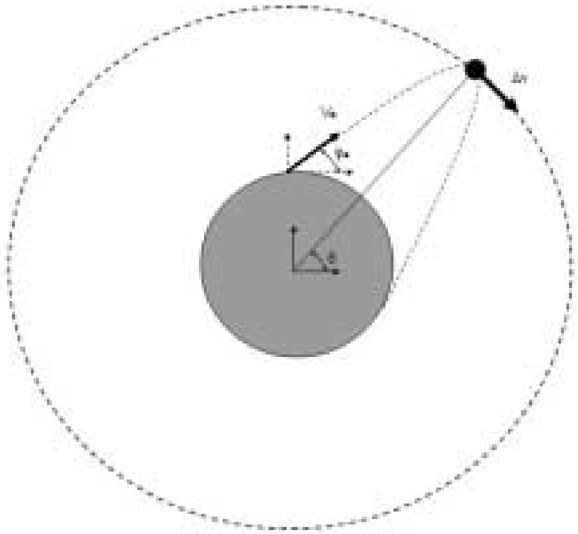


Figure 18: Parameters Defining Energetics of Lunar Launch

As can be observed in Figure 18, the initial conditions are

$$\vec{v}(0) = \begin{pmatrix} v_0 \cos\phi_0 \\ v_0 \sin\phi_0 \end{pmatrix},$$

which means that

$$\dot{r}(0) = v_0 \sin\phi_0 \quad \text{and} \quad \dot{\theta}(0) = -\frac{v_0 \cos\phi_0}{r_0}$$

The potential energy due to the moon's gravity acting on the payload mass of m_p is

$$V = -\frac{\mu_l m_p}{r}.$$

The equations of motion of the payload mass can be obtained using Lagrange's equations of motion, which in the current context are:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{r}}\right) - \frac{\partial T}{\partial r} + \frac{\partial V}{\partial r} = 0$$

and

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\theta}}\right) - \frac{\partial T}{\partial \theta} + \frac{\partial V}{\partial \theta} = 0$$

These take the following form:

$$\ddot{r} - r\dot{\theta}^2 + \mu_l/r^2 = 0$$

and

$$\dot{\theta} = -\frac{v_0 r_0 \cos\phi_0}{r^2}$$

Substitution of the second equation above into the first, produces the equation

$$\ddot{r} + f(r) = 0$$

where

$$f(r) = -\frac{v_0^2 r_0^2 \cos^2\phi_0}{r^3} + \frac{\mu_l}{r^2}.$$

Observing that

$$\ddot{r} = \frac{d\dot{r}}{dt} = \frac{d\dot{r}}{dr}\frac{dr}{dt} = \frac{d\dot{r}}{dr}\dot{r}$$

allows us to integrate this equation as:

$$\dot{r}^2 - v_0^2 \sin^2\phi_0 = 2\int_{r_0}^{r} f(r')dr'.$$

From this equation, we can find the point in the trajectory at which the projectile is no longer moving away from the lunar surface and begins to fall by setting $\dot{r} = 0$. From this we can determine the maximum altitude, r_{max}. The lateral speed at that height is

$$v_{lat} = v_0 r_0 \cos\phi_0 / r_{max}$$

In contrast, the speed required to maintain a circular orbit at a radius of r_{max} is the speed at which centrifugal force balances the force of gravity:

$$v_{orb}^2 / r_{max} = \mu_l / r_{max}^2.$$

The difference $v_{orb} - v_{lat}$ is the supplemental speed (Δv) which would need to be provided by a rocket to maintain the launched payload in circular orbit around the moon. In phase II we plan to build on this analysis to study the tradeoffs between launch angle, proportion of launch covered by chemical rocket vs. electromagnetic gun, etc.

9 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 input 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 organisms, are capable of astonishingly complex results, such as the manufacture of self-assembling capsid proteins, even though they have quite simple genetic codes.

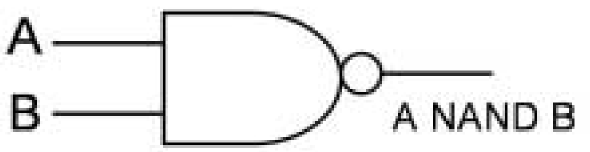
Looking to biology for motivation, we take a minimalist approach to the intelligence aspects of self-replicating robotic factories. Instead of sophisticate microprocessors (which are sensitive to radiation) each robot brain would consist of electromechanical switches, primitive vacuum tubes (without the need for actual glass tubes due to the vacuum of space). Based on the coil manufacturing techniques outlined in Section 6, it is plausible that relay circuits (and hence the equivalent of transistor logic hardware) can be produced in situ. See Figs 19 and 20 for the relationship between individual transistors and logic gates.

These ideas are in line with several modes of thought in the robotics community in the past decade. For instance, Brooks' subsumption architecture [12] is based on a reactive behavior in which sensory data drives robot motion. In Norbert 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 [145]. The work of Tilden on robots capable of surprisingly complex behavior with central control units consisting of a few transistors [57] also encourages us to pursue this direction. Canny and Goldberg [14] explored the idea of minimalism in robotics. This built on the work of Mason and Erdmann [39, 89] 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 twenty 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:

- The robot must translate encoded instructions into tasks consisting of moving

A	B	A NAND B
0	0	1
0	1	1
1	0	1
1	1	0



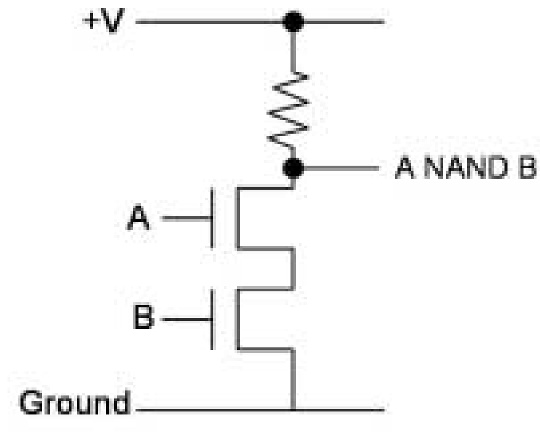


Figure 19: The NAND Gate: truth table, symbol and transistor implementation

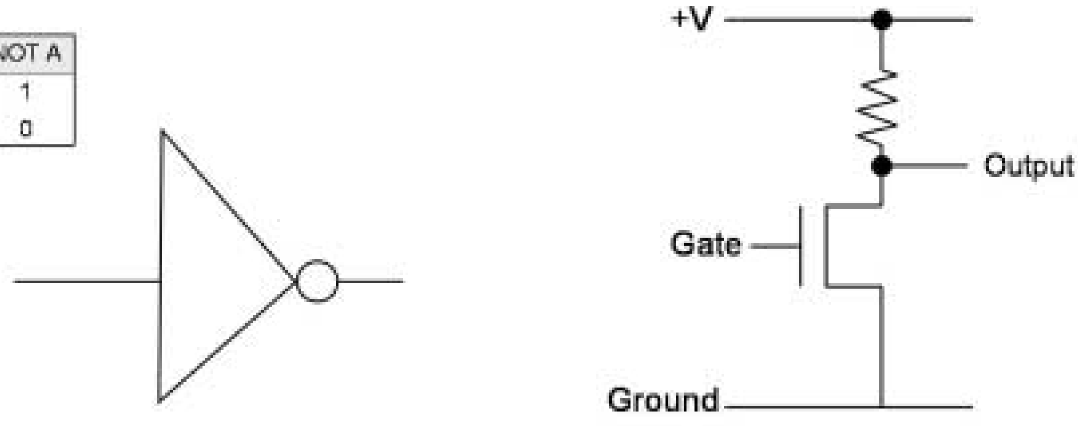
objects and exerting forces;

- The robot must be able to sense and correct its location relative to artificial landmarks;
- The robot must be able to assess if it is damaged, misassembled, and/or not functioning properly;
- The robot must be able to identify all components for which it is responsible to manipulate.
- The robot must transfer all of the above abilities to its replicas.

We believe that all of these tasks can be achieved using networks of large electromechanical relays (each being perhaps the size of a soda can) 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.



A	NOT A
0	1
1	0

Figure 20: The NOT Gate: truth table, symbol and transistor implementation

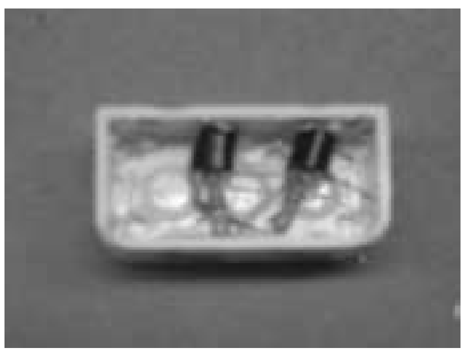


Figure 21: A Logic Gate Embedded in a LEGO Block

Prototypes of self-replicating circuits that take in transistors embedded in LEGO blocks and make functional copies of themselves were implemented in Phase I. The details of these student prototypes are described in the appendices. These constitute three papers which have been submitted for publication in conference proceedings. All three share the common feature that they were constructed from LEGO blocks with embedded logic gates such as those shown in Figure 21. One example of the self-replicating circuits developed by the PI's students is the system show in Figure 22.

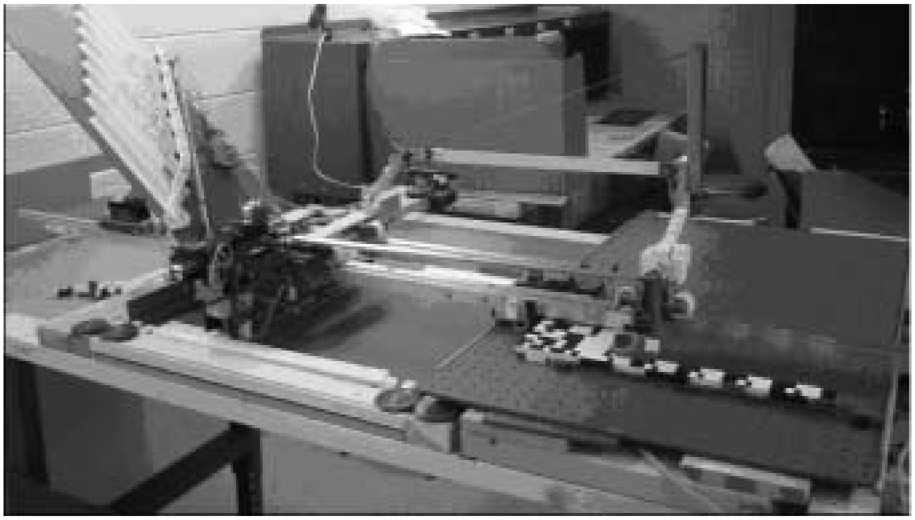


Figure 22: A Self-Replicating Circuit Built from Individual LEGO Gates

10 An Analysis of the Proliferation of Self-Replicating Robots on the Moon

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 electromagnetic launcher 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. Subsection 10.1 models the spreading of self-replicating factories as a degenerate diffusion that evolves on the rotation group $SO(3)$. Subsection 10.2 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.

10.1 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 electromagnetic launcher, 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 a an orientation about $\mathbf{u}(\alpha,\beta)$, means that the complete pose of a robot/factory/electromagnetic launcher system on the lunar surface is described by the 3×3 rotation matrix

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

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 electromagnetic launcher 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 electromagnetic launcher has an expected shooting distance of $0 < d_1 << 1$ 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 electromagnetic launcher 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 cue for establishing the direction of the new electromagnetic launcher replica.

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

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

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 [2]

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

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 [19]

$$X_1^R = \cot\beta\cos\gamma\frac{\partial}{\partial\gamma} - \frac{\cos\gamma}{\sin\beta}\frac{\partial}{\partial\alpha} + \sin\gamma\frac{\partial}{\partial\beta}; \tag{10}$$

$$X_2^R = -\cot\beta\sin\gamma\frac{\partial}{\partial\gamma} + \frac{\sin\gamma}{\sin\beta}\frac{\partial}{\partial\alpha} + \cos\gamma\frac{\partial}{\partial\beta}; \tag{11}$$

[2]For a full description of how to derive this, see [Zhou, Y., "Inverse Problems and Stochastic Models in Engineering", PhD Dissertation, JHU Mechanical Engineering, March 2004].

$$X_3^R = \frac{\partial}{\partial \gamma}. \tag{12}$$

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 electromagnetic launcher orientation, which together define $R = I_3$ (the 3×3 identity matrix).

10.2 Solving the Degenerate Diffusion Equation

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

$$f(R) = \sum_{l=0}^{\infty}(2l+1) \sum_{m=-l}^{l} \sum_{n=-l}^{l} \hat{f}^l_{nm} U^l_{mn}(R) = \sum_{l=0}^{\infty}(2l+1)\text{trace}[\hat{f}^l U^l] \tag{14}$$

where

$$\hat{f}^l_{mn} = \int_{SO(3)} f(R) U^l_{mn}(R^{-1}) d(R), \tag{15}$$

and R denotes a member of $SO(3)$ and $d(R)$ is the volume element of R [19]. Here, U^l is a $(2l+1) \times (2l+1)$ dimensional matrix called an irreducible unitary representation of $SO(3)$ with $l = 0, 1, 2...$ [139, 50, 138]. Its elements are given by

$$U^l_{mn}(R_{ZYZ}(\alpha, \beta, \gamma)) = e^{-im\alpha} P^l_{mn}(\cos\beta) e^{-in\gamma}, \tag{16}$$

where $|m|, |n| \leq l$, and the functions $P^l_{mn}(\cos\beta)$ are generalizations of the associated Legendre functions [139].

Then we use the facts that [19, 50, 139]:

$$X_1^R U^l_{mn} = \frac{1}{2} c^l_{-n} U^l_{m,n-1} - \frac{1}{2} c^l_n U^l_{m,n+1}; \tag{17}$$

$$X_2^R U^l_{mn} = \frac{1}{2} i c^l_{-n} U^l_{m,n-1} + \frac{1}{2} i c^l_n U^l_{m,n+1}; \tag{18}$$

$$X_3^R U^l_{mn} = -in U^l_{mn}; \tag{19}$$

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

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

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

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 electromagnetic launcher 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.

10.3 Numerical Results

By using Fourier Analysis on the rotation group SO(3), we solve the partial differential equation to get the function g(α,β,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

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

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

Comparing Fig.23 and Fig.24, 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.19.2 and Fig.19.3, 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

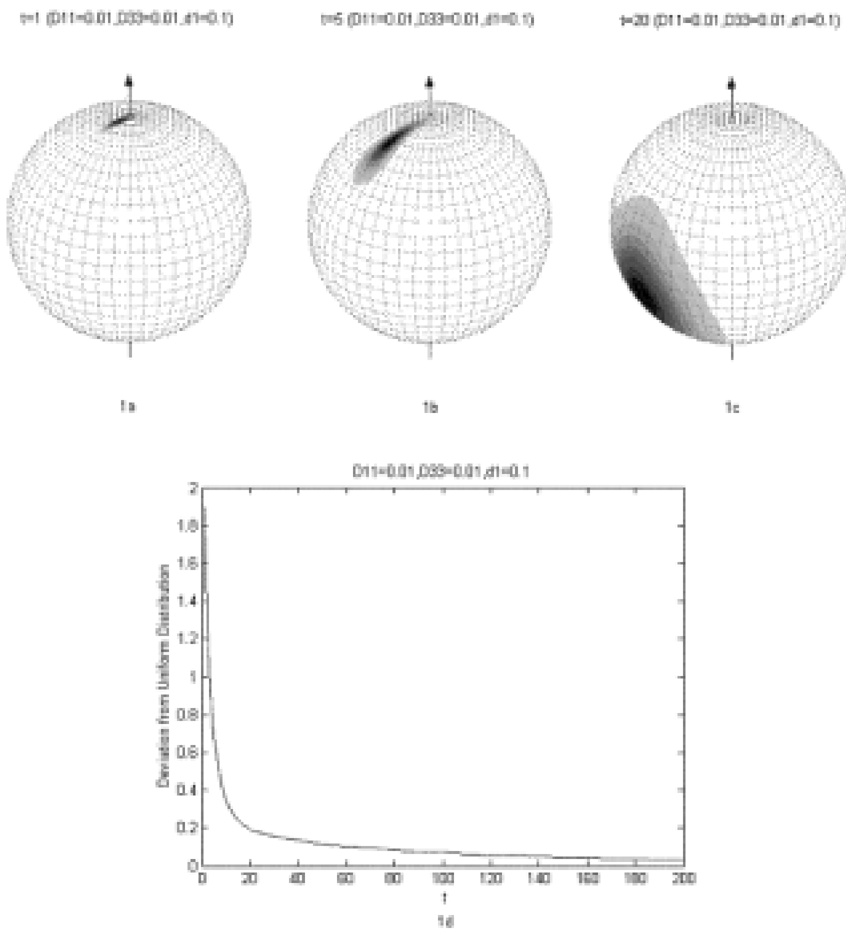


Figure 23: Numerical Results for Diffusion of Self-Replicating Lunar Factories with parameters $D_{11} = 0.01$, $D_{33} = 0.01$ and $d_1 = 0.1$

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.24, 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 electromagnetic launcher 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.

11 Conclusions

This report has shown using a combination of prototype implementations, analysis, and literature survey that self-replicating lunar factories do in fact appear to be feasible. A road map for the novel recombination and integration of existing technologies

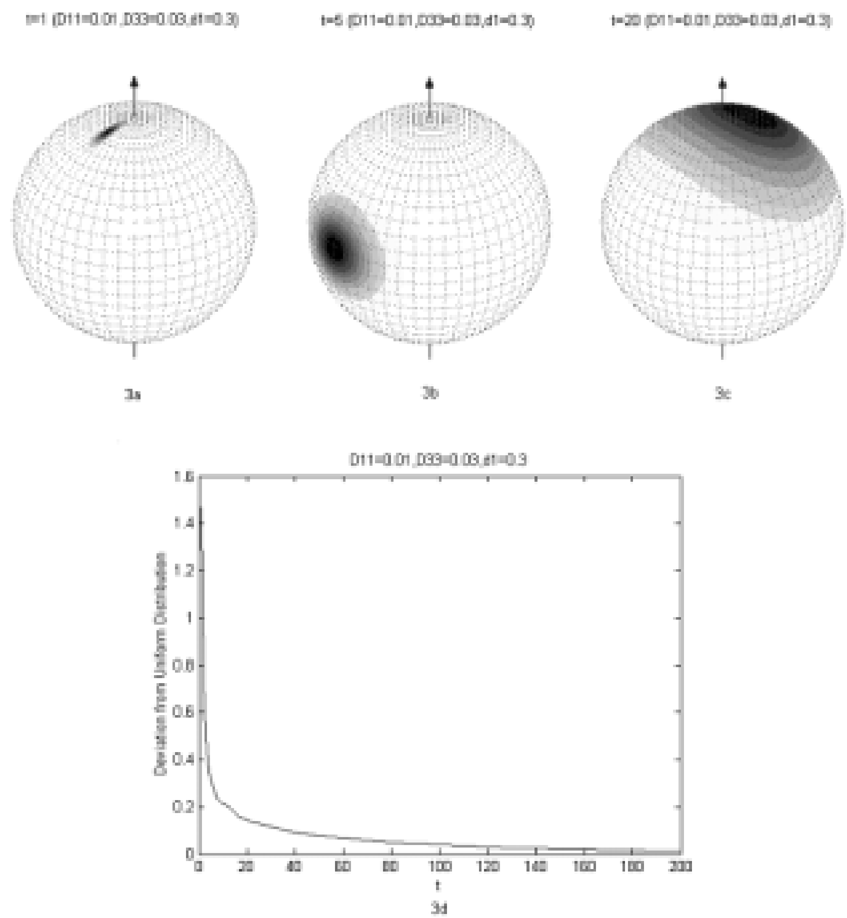


Figure 24: Numerical Results for Diffusion of Self-Replicating Lunar Factories with parameters $D_{11} = 0.01$, $D_{33} = 0.03$ and $d_1 = 0.3$

and systems into an architecture that can be implemented in the next ten to forty years is provided. The first step toward realizing this goal is to meet the ambitious objectives articulated in the Phase II proposal that follows this Phase I award.

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APPENDIX

Drafts of articles which have been submitted for publication during this phase I award are attached as appendices. This material has minimal overlap with that presented in the main body of the report.

An Autonomous Self-Replicating Robotic System

Jackrit Suthakorn, Andrew B. Cushing, and Gregory S. Chirikjian, *Member, IEEE*

***Abstract*—The concept of self-replicating machines was introduced more than fifty years ago by John von Neumann. However, to our knowledge a fully autonomous self-replicating robot has not been implemented until now. Here we describe a fully autonomous prototype that demonstrates robotic self replication. This work builds on our previous results in remote-controlled robotic replication and semi-autonomous replicating robotic systems.**

***Index Terms*—Self-Replication, Artificial Life, Robot, Modular Robots.**

I. Introduction

IN this paper, we develop a physical prototype capable of fully autonomous self replication in a laboratory setting. This work builds upon our previous results in remote-controlled robotic replication presented in [1], and a semi-autonomous replicating robotic system presented in [2]. The new prototype uses two light sensors in its navigation system to detect objects and to also track lines. Our prototype is constructed from modified LEGO Mindstorm kits in which the electrical connections are enhanced. Magnets and shape-constraining blocks are employed to aid in the aligning and interlocking of the replica's subsystems. We also discuss the motivation for studying self-replicating systems and review previous works. Finally, results of experiments with our prototype system are discussed.

A. Motivation

People have imagined for years a factory that could autonomously replicate itself for multiple generations, requiring neither people nor the monstrous machinery typically associated with a factory. Over the recent decades, outer space has been mentioned as one potential application for such self-replicating robotic factories (see e.g., [3-5]). However, enormous technical barriers must be overcome before these systems can become feasible. The purpose of the current work is to take one small step toward realizing this goal.

In contrast to self-reconfigurable robotics [6-10], self-replication utilizes an original unit to actively assemble an exact copy of itself from passive components. This can result in exponential growth in the number of robots available to perform a job, thus drastically shortening the original unit's task time.

B. Previous Efforts in Mechanical Self-Replicating System

Von Neumann [11] 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, nanotechnology, macromolecular chemistry, and computer programming (more details in [12].)

In the late 1950's, Penrose performed the first recognized demonstration of a self-replicating mechanical system [13]. It consisted of passive elements that self-assembled only under external agitation. This is similar in many ways to the modern work of Whitesides [14], only at a different length scale.

More than 20 years after Penrose, NASA established a series of studies on the topic of "Advanced Automation for Space Missions" [3]. These studies investigated the possibility of building a self-replicating factory on the moon. References [15-19] also outlined strategies for space utilization. Recently, research on robots that are capable of designing other machines with little help from humans has also been performed (see [20] and references therein). This relies on the use of rapid prototyping technologies.

II. Design and Descriptions of an Autonomous Self-Replicating Robot

The robot and its replicas each consist of four subsystems: controller, left tread, right tread, and gripper/sensor subsystems. All subsystems are connected to others using magnets and shape constraints. Figure 1 shows an assembly view of the robot.

The controller subsystem is made up of a LEGO RCX programmable controller fit inside a chassis. The chassis's sides are used to connect to the left and right treads. Each side has a set of magnets, a set of shape-constraining blocks, and a set of electrical connections. The front end of the chassis is designed to attach with the gripper. The front end also has a set of magnets, a set of shape-constraining blocks, and a set of electrical connections, which transfer electrical and electronic signals from the controller to the gripper's motor and the navigating sensors installed on the gripper subsystem.

The magnets and the shape-constraining blocks are used in collaboration to aid aligning and interlocking subsystems. On each chassis side, the magnets are symmetrically placed in

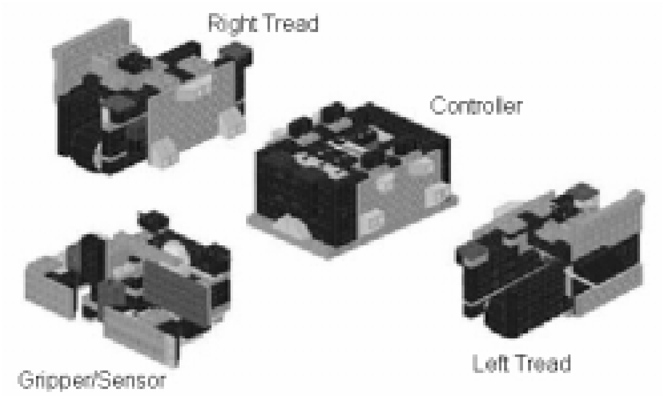

Fig. 1. An assembly view of the self-replicating robot.

opposite polar directions to each other. This is to protect against incorrect positioning of the subsystems. The concept of using the magnets (with different polarizations) and shape-constraining blocks was influenced by the self-complementary molecules of Rebek [21]. Figure 2 illustrates the concepts of using the polar magnets and shape-constrained blocks to align and interlock subsystems. By design, it is very difficult for these connectors to misalign.

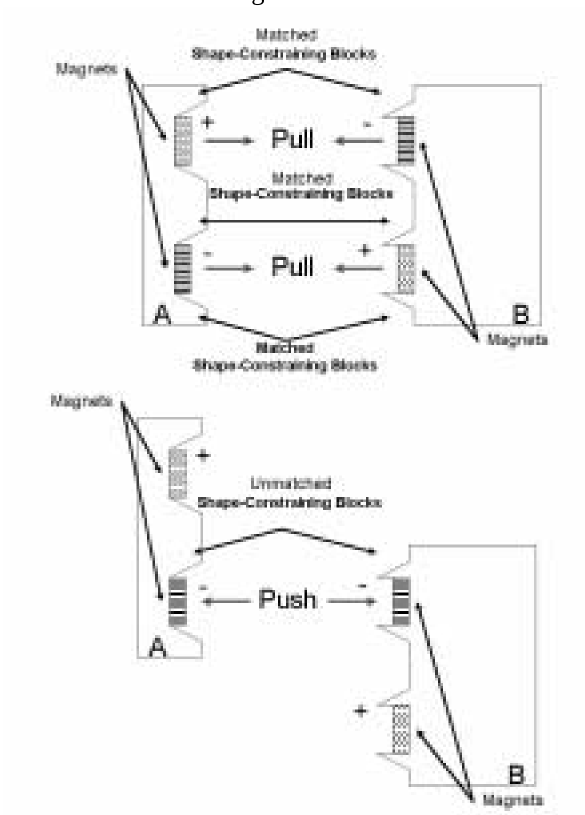

Fig. 2. This diagram illustrates the concept of using polar magnets and shape-constraining blocks (top: correctly aligning, and bottom: incorrectly aligning.)

The left and right tread subsystems are designed to be identical to each other, with the purpose of reducing the system's design complexity. A tread subsystem hosts a rubber tread with a driving gear system, a 9V LEGO DC motor, and a light-reflective pad which helps the original robot's navigation. One side of the tread has a set of magnets, a set of shape-constrained blocks, and a set of electrical connections, all of which correspond to the side of the controller subsystem. On the other side, the tread has a wedge which is fitted to the gripper. The wedge is used during the tread subsystem's transferring and assembling processes. Figure 3 shows how the original robot grasps the tread subsystem, and Figure 4 shows the connections located between the controller and tread subsystems.

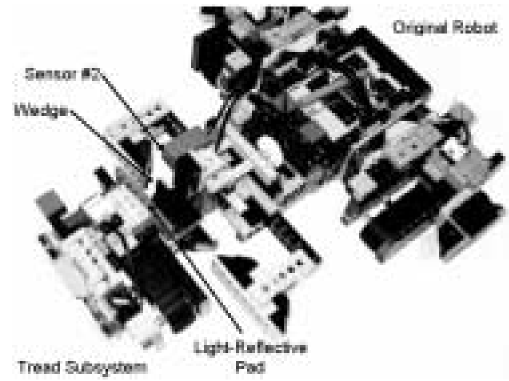

Figure 3: The original robot grasps the tread subsystem.

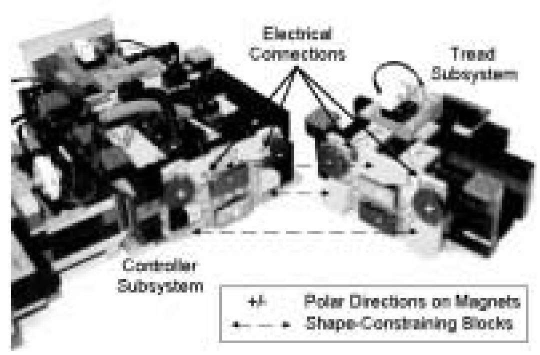

Figure 4: The connections located between controller and tread subsystems.

The gripper/sensor subsystem is comprised of a 9V LEGO DC motor, a set of rack and pinion gears used to drive the left/right fingers of the gripper, a set of magnets, a set of shape-constrained blocks, a set of electrical connections, and two light sensors (one is pointed downward, and the other is pointed forward).

The set of magnets, shape-constraining blocks, and electrical connections are attached to their corresponding part, on the front side of the controller subsystem. The left finger of the gripper is designed in a wedge shape to be fitted with the gripper in any identical robot. This wedge is used in the same manner as in the tread subsystems during assembling processes. Figure 5 shows how the original robot grasps the gripper/sensor subsystem, and Figure 6 shows the connections located between gripper/sensor and controller subsystems. The two LEGO light sensors are employed in the robot's navigation system. The first light sensor (pointed downward) is used to detect the blue painted lines and silver acrylic spots on the experiment surface. The second light sensor (pointed forward) is used to detect objects (the subsystems of the replica) which the robot runs into.

The experimental area is a 2m x 3m area made of white colored paper with lines and spots painted in blue and silver acrylic colors. The original robot starts at the initial position,

and the replica's subsystems are at their locations. Figure 7 shows the experimental area with locations of the replica's subsystems and the initial position of the original robot.

III. CONTROLS AND PROGRAMMING

The prototype robot is a fully autonomous system. Figure 8 shows the control architecture of the robot. The robot and its replicas, using the LEGO light sensor No. 1 (pointed downward), is capable of tracking the blue lines, and it can recognize the assembling spots, painted in an silver acrylic. The sensor detects and returns different analog values, corresponding to different colors. The robot tracks the painted lines to navigate between positions. Once the robot detects the assembling spot, the robot begins the assembling process. The LEGO light sensor No. 2 (pointed forward) returns an analog value once it detects a light-reflective pad attached to the tread and gripper/sensor subsystems. This notifies the robot to begin grasping the detected subsystem.

The grasping process consists of an aligning push toward the subsystem, and closing the gripper to grasp the subsystem. On the other hand, the assembly process consists of opening the gripper to release the subsystem, and an aligning push forward to snap the subsystem to the controller. Figure 9 shows the original robot grasping a subsystem, and moving toward an assembling spot, in silver acrylic, along the blue line.

The programming of the prototype is described here. The code is programmed on a PC and transferred through a LEGO infrared program-transferring tower. In the order in which events take place in the replication process, the programming is separated into seven stages: 1) replication process is activated, 2) line tracking and searching for a subsystem, 3) grasping the subsystem and changing to a new path which leads to the next step, 4) line tracking and searching for the assembly location, 5) assembling the subsystem to the controller and changing to a new path, 6) the new path leads to the next subsystem, 7) The final step loops back to steps 2 through 6 so the process repeats indefinitely. Figure 10 illustrates the programming flowchart of the self-replicating robot system.

IV. EXPERIMENTS AND RESULTS

The following is a step-by-step procedure for our autonomous self-replicating robot system (Figure 11 is a photographic representation of these steps):

1. The original robot starts following the line from the starting point to the first subsystem using sensor No. 1.
2. Once light sensor No. 2 detects the first subsystem (right tread), the original robot begins the grasping process and grasps the right tread subsystem.
3. After the grippers are closed the original robot turns to the right until it detects a line.
4. The original robot follows the second line until it reaches the assembly location.

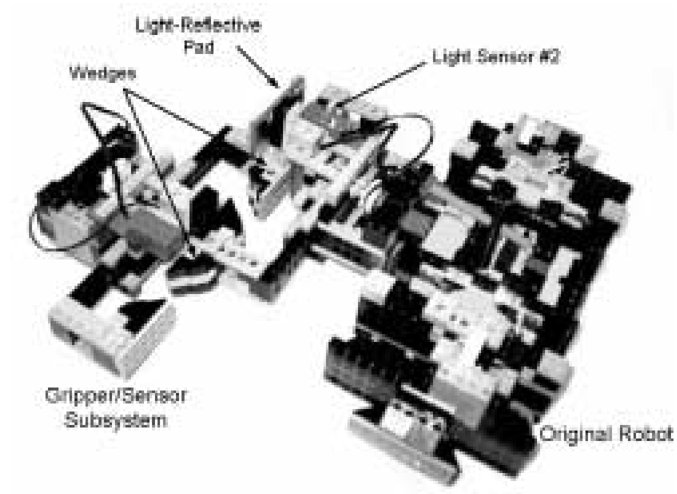

Fig. 5. The original robot grasps the gripper/sensor subsystem.

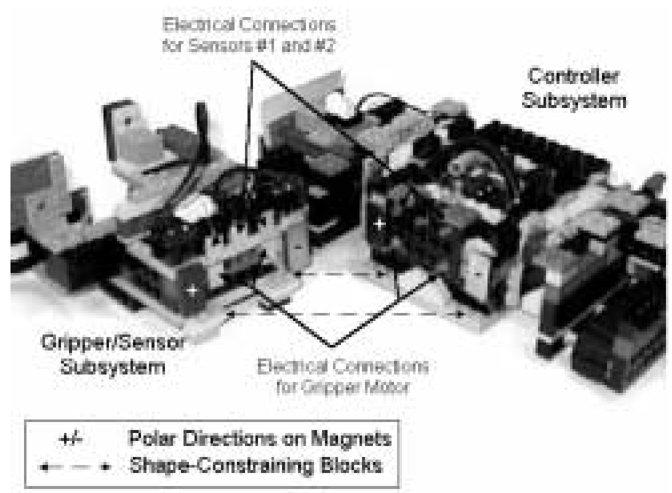

Fig. 6. The connections located between gripper/sensor and controller subsystems.

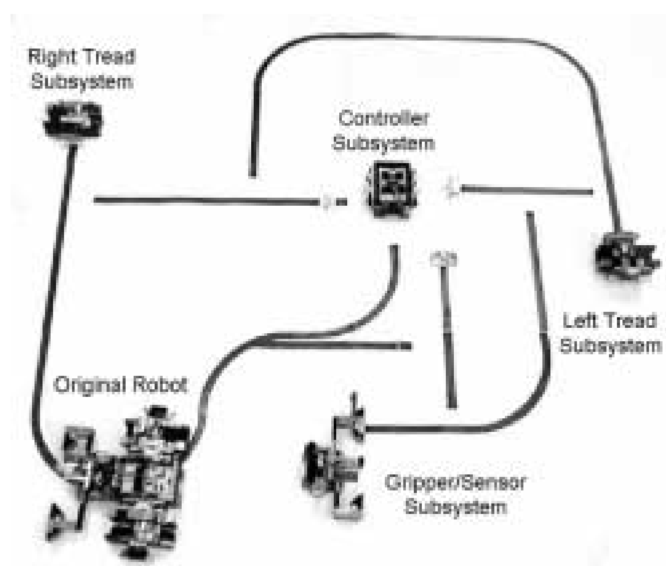

Fig. 7. A map of the experimental area.

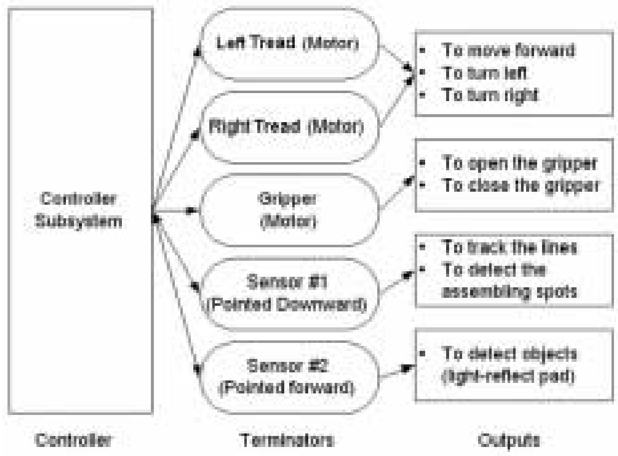

Fig. 8. The control architecture of the autonomous self-replicating robot.

5. When light sensor No. 1 on the original robot detects the silver acrylic spot (the assembly location), the robot stops, and begins the attaching process.
6. The original robot opens the grippers, and gives a final push to secure the right tread subsystem to the controller subsystem.
7. The original robot then backs up and turns to the left until it detects a line value on sensor No. 1.
8. The original robot follows the line until it reaches the left tread subsystem.
9. Once light sensor No. 2 detects the second subsystem, the robot will stop, and begin the grasping process by closing its gripper around the left tread's wedge.
10. The original robot turns right until it detects the next line.
11. The original robot will follow the second line until it reaches the assembly location.
12. The original robot opens its gripper to release the left tread subsystem.
13. The original robot gives a final push on the left tread subsystem to help secure it.
14. The original robot then backs up and turns left until it detects the next line, using sensor No. 1.
15. The original robot follows the line to the final subsystem.
16. Once it reaches the gripper/sensor subsystem, it stops, and begins the grasping process.
17. The original robot closes its gripper, and turns right until it detects a line value with sensor No. 1.
18. The gripper/sensor subsystem is now transferred to the assembly location.
19. Once the original robot reaches the assembly location it stops, and opens the gripper.
20. The original robot backs up and turns left until sensor No. 1 is a line value.
21. The original robot then follows the line back to the starting point, and is ready to replicate again.
22. The completed replica self-activates (20 seconds after completion) and begins following the line to the starting point.
23. Once each robot reaches the starting point, it begins the replication procedure again.

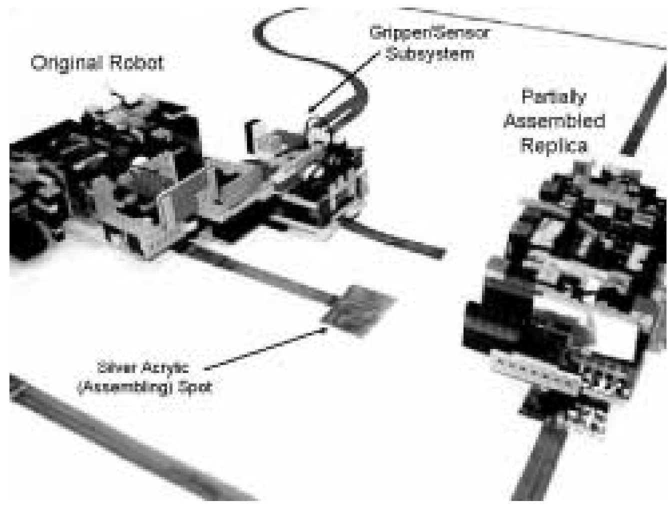

Fig.9. The robot is searching for the assembly location while holding the replica's gripper/sensor subsystem.

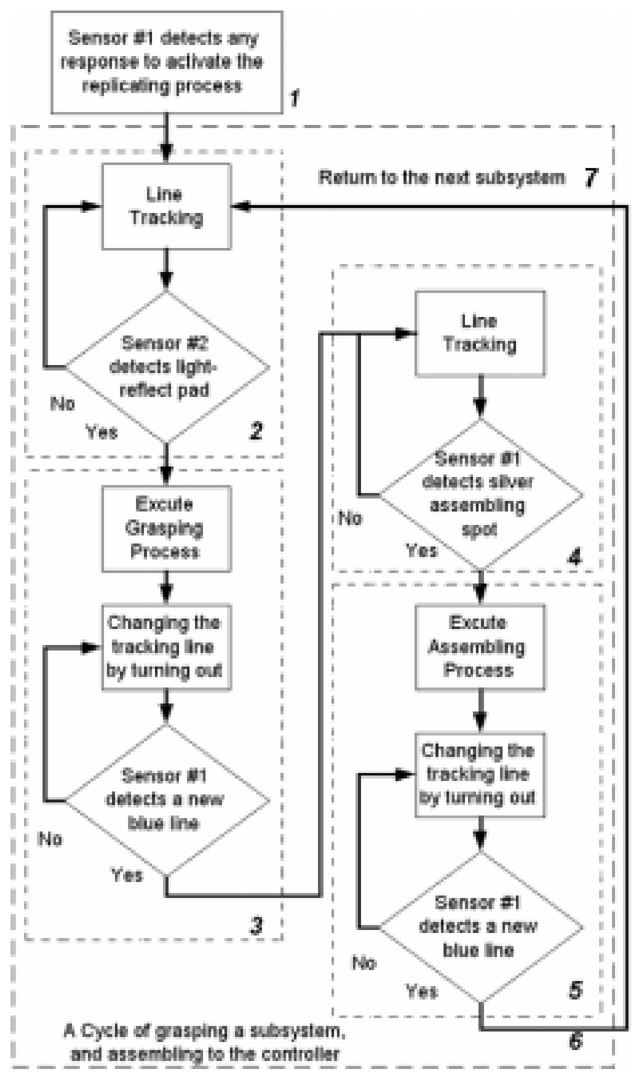

Fig. 10. The flowchart of the self-replication process.

The replication process takes two minutes and fifteen seconds per cycle. Although each subsystem is required to be placed in its starting location, errors in initial position and

orientation are not very critical. We found slight errors during the grasping process in a few experiments caused by improper placement of the subsystems. Overall, the system is robust and very repeatable.

V. CONCLUSION

An autonomous self-replicating robot prototype has been constructed and tested. It uses two light sensors in its navigation system to detect objects and also to track lines. Magnets and shape-constraining blocks are used to aid in aligning and interlocking the subsystems of the replica. As a result, the robot is capable of automatically assembling its replicas. All the replicas are also capable of completing the same replicating process. We believe that this prototype is the world's first fully functional autonomous self-replicating robot.

ACKNOWLEDGEMENT

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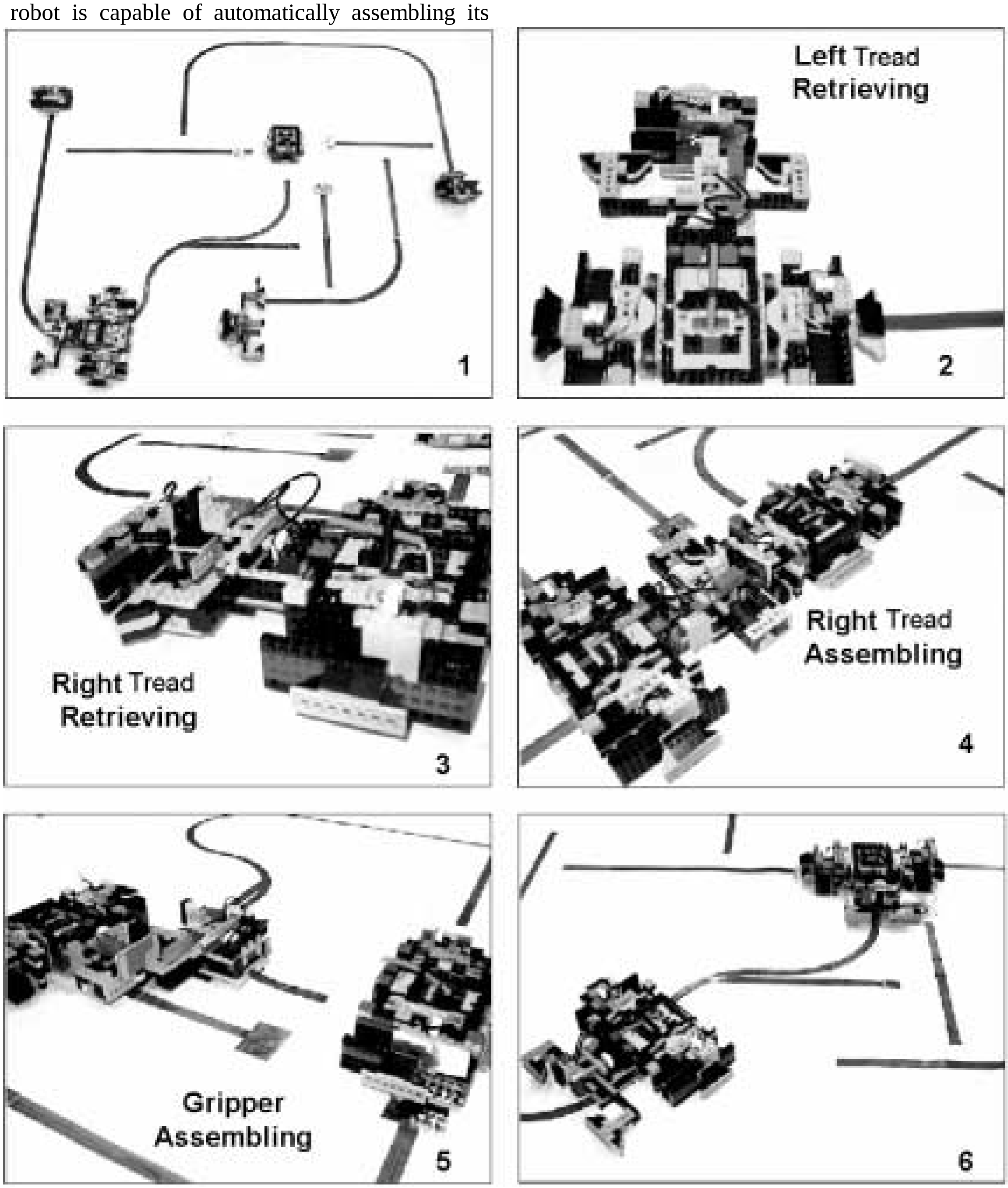

Fig. 11. Self-replication process: 1) the original robot begins at the initial position with every part placed in their position. 2) The robot detects the right-tread subsystem. 3) The robot grasps the right-tread subsystem, and attaches it to the controller. 4) In the same manner, the robot performs the assembly of the left-tread subsystem. 5) After the robot grasps the gripper/sensor subsystem the robot transfers the subsystem to the next assembly step at the controller. 6) After being fully assembled, the replica is self-activated, and ready to replicate just like the original.

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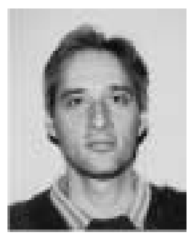

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Dr. Chirikjian is the recipient of a 1993 National Science Foundation (NSF) Young Investigator Award, a 1994 Presidential Faculty Fellow, and a 1996 ASME Pi Tau Sigma Gold Medal.

A Minimalist Parts Manipulation System for a Self-replicating Electromechanical Circuit

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Abstract

In this paper, we describe a fully autonomous, self-replicating, electromechanical circuit, and the minimalist manipulation system that the circuit uses as a substrate in order to function. In the context of a class project at JHU, we designed and built a prototype system consisting of basic electronic components and motors which had the ability to build a replica of its own control circuit. This artificial "self-replicating electromechanical intelligence" has the ability to identify the proper electronic components required, translate encoded instructions into mechanical tasks that create a replica of itself, and transfer all intelligence functions to the replica. The design is scalable and the components are modular, allowing many different levels of intelligence to be replicated. This concept is one of many which we are investigating to enable self-replicating robots to perform complex behaviours. The ultimate application of such robots is as subsystems in a self-replicating robotic factory. The presented prototype demonstrates active mechanical replication of the physical hardware required for intelligent behaviours, which is an initial step in the direction of self-replicating robots.

Keywords: Self-Replication, Robot, Modular Robot, Artificial Life; Electromechanical Intelligence

I. INTRODUCTION

In this paper, a minimalist manipulation system is described in which actuated bins allow electronic logic components to be released under the command of a control circuit. The control circuit is composed of the same kind of components held in the bins, and controls their release in such a way that an exact functional copy of the control circuit is constructed. The proper design of passive railing (or fences) causes parts to be channelled to the proper location as they flow down an incline under the action of gravity. Each block of electronic components has a color code which is read and fed into the circuit itself for interpretation. Hence, this is an example of a control circuit which demonstrates self-replication by self-inspection. Of course, the circuit does not reproduce the electromechanical substrate (manipulation system) on which it acts. This is in analogy to the way animals in a forest reproduce without necessarily contributing to the reproduction of the vegetation from which they draw their nutrition.

Self-replication in both biological and artificial systems has been studied extensively. The concept of self-replication is one of the central features of living cells. The mechanisms involved in biological replication are currently being studied by researchers in order to understand the mechanisms of life, how viruses attack the immune system, and how the body uses basic chemical building blocks for growth and regeneration in an efficient manner. Whereas the mechanisms of biological self-replication are often emulated, alternative paradigms do exist.

Biologically-inspired research areas devoted to the study of self-replication include "artificial life" and evolutionary algorithms [Gardner 1970; Langton 1984,1986; Lohn 1997; Sipper 1998]. These fields are concerned with theoretical and algorithmic ideas of self-replication. Self-replicating systems studied in those fields are geometric and algorithmic patterns that replicate through rule sets generated on a computer. Von Neumann introduced the theory of self-replicating automata in the 1950's [von Neumann 1962]. His idea for self-replicating automata is based on ``universal replicators" which in principle would have the ability to read any set of instructions and convert them into commands that result in the assembly of copies of the original machine, as well as passing on a copy of the instructions for making copies. In theory, the replica would then have the ability to replicate and the process would continue. No such machine has ever been built. In contrast, the concept of non-physical self-replication has merged into many other areas of research including cellular automata, nanotechnology, and computer viruses [Sipper 1998; Freitas 2004].

Until recently macroscopic physically self-replicating systems have been limited to self-assembly systems that consist of passive components which self

assemble under naturally occurring forces [Penrose 1959; Whitesides 1995; Cohn 1995]. Such systems use no sensing, actuation or information processing, and hence are unable to demonstrate directed intention for assembling a replica. For a robot to be self-replicating, it must be able to reproduce a functional replica by one or more robots of the same kind over one or more generations. This process can be achieved by directly replicating and indirectly replicating systems. Directly replicating robots actively assemble exact replicas of themselves. Indirectly replicating robots produce one or more intermediate robots that will in turn produce the replica of the original.

The concept of self-replicating robots, if proven feasible, could revolutionize the way robots are used. NASA had interest in the idea in the 1970's and early 1980's and investigated self-replicating systems for space applications [Freitas 1982] and interest persists to the present day [Chadeev 2000; Freidman 2002]. They proposed self-replicating factories on the moon and other conceptual studies for utilization of replicating robots in space. Although the idea of self-replicating robots started as science fiction without concrete designs and prototypes, that age is coming to a close, and tangible technologies which will allow such systems to exist are becoming reality.

Recently our lab has built prototypes of remote controlled as well as semi and fully autonomous self-replicating robot systems in which the robot controller was one of several prefabricated subsystems [Chirikjian 2002; Suthakorn 2003 (a,b)]. These prototypes have demonstrated the feasibility of self-replicating systems from fairly complex building blocks and examined issues in mechanics, sensing, and task execution in self-replicating systems. The current work examines how control circuitry for such systems can itself be constructed by self-replication. This is a very different problem than the one examined previously by Chirikjian and Suthakorn in which mobile robots navigate through a structured environment to pick up pieces and assemble replicas of themselves from subsystems. Here the emphasis is construction of one of these subsystems (the controller) from the most basic parts by self-replication.

A number of other areas related to self-replicating systems have been investigated in the literature. The area of modular-self-reconfigurable systems has received attention [Fukuda 1990,1991; Murata 1994; Chirikjian 1996; Hosokawa 1999; Kotay 1999; Saitou 1999; Yim 2001; Stoy 2002], as have the topics of self-diagnosis and repair [Russel 1975 (a,b)] and novel rapid prototyping technologies which could be used in future self-replicating systems [Lipson 2000; Hornby 2001; Fuller 2002]. The development of replicating software for metamorphic robots also has been investigated [Butler 2002], as have cybernetic machines [Hasslacher 1995; Wiener 1967].

In this paper we take a closer look at indirectly replicating robots and examine one of the paradigms, self-replicating electromechanical intelligence. The goal is to design a circuit that self-replicates by issuing commands to electromechanical actuators. Ultimately we expect that this will be a technology that can be applied to the concept of a simple self-replicating lunar robotic factory. Therefore, instead of microprocessors and other microelectronic devices the system was built from electromechanical motors and individual electronic components including resistors, capacitors, discrete transistors, and switches which in principle could be manufactured in situ.. Philosophies focusing on minimalism in robotics like the one presented here are not new to the field [Erdmann and Mason 1988; Canny and Goldberg 1995]. For our application, the minimalist approach works quite well because the robot task is unchanging which eliminates the need for re-programming.

The remainder of this paper is structured as follows: Section II describes the design of both mechanical and electronic components of the system. Section III discusses how this design might be improved, and future work which may build on the work reported here, which was done as a class project in the last author's Mechatronics course (The authors are the students and TAs who worked on this project.) Section IV presents our conclusions.

II. DESIGN

Our goals in this work are to develop an electronic circuit that self-replicates out of basic components and to demonstrate the feasibility of some of the concepts stated in the introduction. In this context, the manipulation system consiting of motorized wheels, actuated bins, inclined board and fences is viewed as a substrate on which the circuit acts. Since these elements are not part of the circuit itself, demonstrating reproduction of the manipulation assembly is not part of the current work. Our very simple design meets the following criteria: (1) The circuit translates encoded instructions into tasks such as moving objects and exerting forces; (2) It is able to identify all the components which it is responsible to manipulate; (3) It is able to make copies of itself and transfer all of the above abilities to the replicas. To satisfy the above criteria, the whole system consists of three main components: the control circuit, a code for replication (which is integrated in the circuit), and a mechanical means to build the replicas (which is the manipulation system acted on by the control circuit).

II *A. Mechanical Design*

The mechanical system is required to manipulate the basic electrical components for the replication of the circuit. To eliminate the need for complicated timing circuits to control movements involved in picking and placing pieces, gravity was employed to deliver the circuit elements to their proper location. Additionally, we built our prototype using modified LEGO Mindstorm kits. This allowed us to take advantage of the modularity within the Lego design and avoid the complications associated with machining complex parts. An overview of the mechanical design is shown in Figure 1.

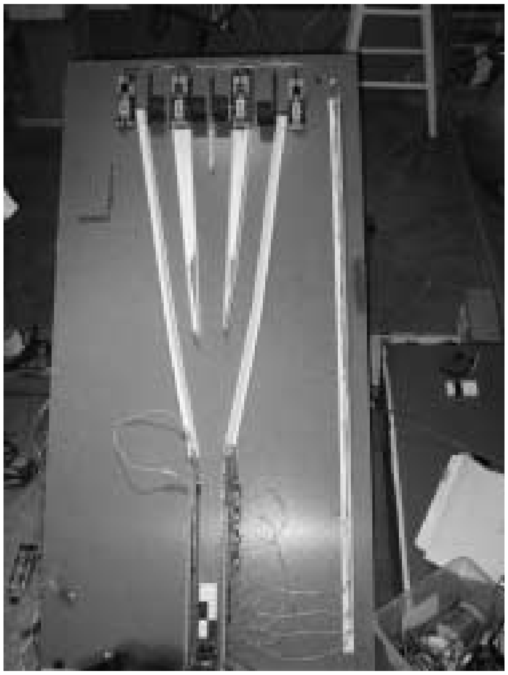

Figure 1: Overview of the Manipulation System on which the Self-Replicating Circuit Acts

With this design, hoppers are placed at the top of an inclined plane to hold the modular electronic components used to construct the circuit replicas. Each hopper has a motor and a feeding wheel that is activated when a module needs to be released. Each module is a 4x4 LEGO block with two transistors and an electrical connection on each of the four sides. When released, a module will slide down the inclined plane and line up in a track. Once in the track, the modules will be pushed together by gravity and the weight of the oncoming modules. The two primary challenges with the gravity fed system are keeping the blocks properly oriented as they fall and making good electrical connections between the modules after they stack up. After experimenting, rails were used to keep the pieces falling straight. In order to insure good electrical connections, thin spring-loaded wires were appended to the front of module. These wires act as springs and compress against the backside of the previous module to ensure an electrical connection is made as the module falls into place. Additionally, connections on the sides of the module are needed to activate the appropriate hopper and obtain power for the reader, as explained in the following paragraphs. A detailed view of the circuit is shown in Figure 2.

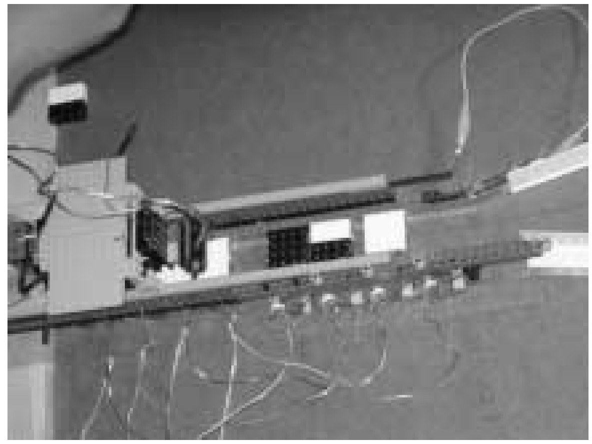

Figure 2: View of the Reader, Modules and electrical connections

Sufficient contact on the module sides is easily obtained by placing small magnets inside the modules. To simplify the design, our circuit is broken into modules that also serve as the encoding. Each module has a set of black and white colors that are read by the control circuit. Using two colors per block requires a circuit that can distinguish between four combinations (black black, black white, white black, and white white). Three colors per block would have led to nine combinations. Using our design, it takes four pairs of transistors to distinguish the four combinations and it would have taken nine sets of three to distinguish between the nine combinations. In other words, the circuit is scalable. Two colors were chosen to keep with the design simple.

The next component of the system is the code reader for the modules, shown in Figure 2. The reader is equipped with two light sensors and provides voltage to the power block (2x4 LEGO block just before the first module) connected to the control circuit on the lower track. The two light sensors are mounted on its front and have their own variable speed control for calibration purposes. The light sensors that come with the Lego kits are too complicated to use with a very simple control circuit. Each sensor contains many transistors and specific timing must be maintained for them to read properly. Instead of using these sensors, a simple light detector was built with adjustable threshold brightness. Any amount of light brighter than the threshold leads to an output of zero volts and any amount dimmer than the threshold leads to a high output voltage. For our prototype we chose to use two colors per block and black and white encoding on our modules since they are easily distinguished by a light sensor.

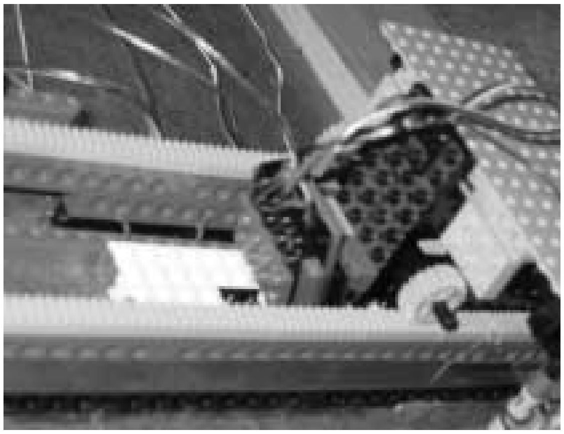

Figure 3: View of the reader and light sensors

The reader climbs a track just above the controlling circuit reading the black and white blocks. Gears are used as drive wheels, riding on a rack (flat, toothed rail), to make climbing the incline possible. The reader starts its motion at the first of the four blocks, and the light sensor sends a voltage signal to the control circuit based on the color combination of each module. This voltage activates the appropriate hopper so that a replica of the module which is read by the light sensor is released and dropped into the lower track. Connections on the right sides of each module run to the hopper that contains its replica. By placing the replicas in the same track as the original circuit an easy front to back electrical connection on the modules allows the light sensors to read and activate the new circuit after the original is read. The signals are simply passed through each block and into the next. Since the reader will encounter the new circuit after it has finished reading the original circuit, it can easily read the second new circuit and build a third copy.

In theory, as many copies could be made as will fit in the track. The decision was made that if we were to keep replicating, the original circuit should not be used as the controlling circuit after the first copy is made. In other words, control needed to be transferred to each new circuit as it was read. To solve this problem, all the outputs from all the circuits are connected to the hoppers at the same time however power is only given to the circuit that is currently being read. This is accomplished by power rails along side each circuit position. The reader then drags a wire along these rails applying power to the rail corresponding to the circuit it is reading. In Figure 3, the yellow wire supplies power to the rail.

II B. Circuit Design

The control circuit must be able to read a code that will control the mechanical element of the robot for retrieving and delivering the circuit components for our replica. In this case, the reader must send a voltage signal to the four-module circuit within the LEGO blocks, which in turn activates the appropriate hopper motor that drops the replica module. A flow chart is shown in Figure 4 and a schematic diagram of the circuit is shown in Figure 5. The reader drive circuit is a variable voltage source connected to a drive motor. Each light sensor has a photo-resistor that varies the output of a voltage divider. If the voltage divider output is below 0.7V, the transistor will be on and the out put to the sensor will be 0V. If the voltage divider output is below 0.7V, the transistor will be off and the output of the sensor will be 9V. The circuit within the LEGO blocks is a simple set of four AND gates. NFETs and PFETs are used since they turn on with the opposite voltages of each other. The four AND gates cover each of the four input cases (11, 10, 01, 00).

III. IMPROVEMENTS AND FUTURE WORK

After several trials, we experimentally proved that the electronic circuit self-replicates and transfers control to the replica. However problems did arise. The largest problem was making connections between the circuit elements after they were dropped. We found that the external contacts of the modules needed some amount of pressure to make a good electrical connection. This may be partly due to the tendency for solder to oxidize or due to some remaining solder flux on the surface of the contact. In practice this meant that the end-to-end connections that pass the sensor inputs did not always work. It also meant that the side contacts needed more than a simple springy wire to make a connection. In order to alleviate the connection problem on the top and bottom of modules, springs made of wire were coiled around the front of the circuit blocks in order to increase the probability of making a connection with adjacent circuit blocks. Although this solved most of the connection problems with the vertical contacts, spacing was critical. If the springs left too large of a gap, the light sensor would read the springs as input and turn on a white-white motor at the wrong time. Hence, the possibility for generating mutations of the original circuit exists.

In order to reduce this problem, a more complicated side connection device was developed, to ensure good connections on the modules sides. Magnets placed inside the modules on one side created a solid connection to the metal strip that gives each circuit individual circuit power. However, this meant that an adjustable mechanism needed to be designed to provide pressure to the modules contact on the opposite side, while allowing the modules to slide into place. A spring-like wire lever was implemented, incorporating just enough stiffness to make good contact, but not enough to hinder the sliding of the modules. This too, had critical implementation issues including lever placement, length, and stiffness. An unbalanced combination would start to slow the fall of the

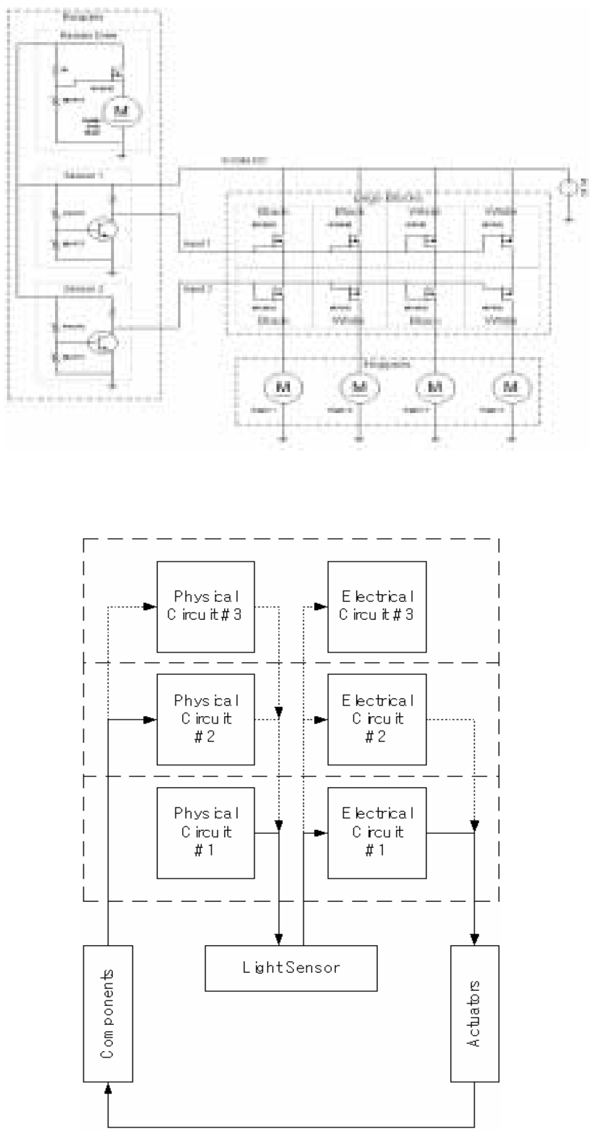

Figure 5: Schematic of Self-Replicating System. Note that the circuit acts as a physical encoder of black and white colors and as an electrical circuit.

modules in the track, sometimes not allowing them to fall into place. The more pressure, the better the electrical connection but the sooner the pieces would stop. The connection mechanism works well with the overall prototype design, but further improvements in the consistency of the device are being examined. Therefore, several connection designs are being investigated for future prototypes. One such design employs a mechanism to squeeze the circuit once it is built, making the connections reliable.

In addition to the connection improvements, we also affixed a light source above the light sensors. A small halogen bulb was fixed onto the reader, slightly above the light sensors. This concept eliminated reliance on ambient light and made calibration easier.

Some improvements to design of the entire system are also being investigated. Ideally, we would like to drop the old circuit out of the bottom of the device after a new one is built and return the reader to the original start position. This would allow replication until the hoppers run out of parts. Additionally, a future prototype for a two-dimensional circuit will take the circuit complexity to the next level.

IV. CONCLUSION

A simple self-replicating electromechanical circuit has been designed and a prototype has been built. The system was built from electromechanical motors and individual electronic components. The circuit self-replicates by issuing commands to electromechanical actuators that assemble the electrical components of the replica. After replication of the circuit, the control of the replication process is transferred to the new replica. Using a simple modular design, the system can be scaled to replicate circuits of greater complexity. These circuits could be implemented in the future as part of an indirectly replicating robot system or multifaceted self-replicating robotic factory. The successful implementation of an active self-replicating electromechanical circuit described here is one step in the design of robots capable of self-replication from the most fundamental components.

ACKNOWLEDGEMENTS

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Construction of a Prototype of Self-Replicating Electromechanical Intelligence

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Summary. The construction of an electromechanical prototype, a so-called self-replicating intelligence system, is presented in this paper. In principle this system can replicate both its mechanical codes and the electrical control circuits that convey the commands. By reading the codes via optical reader, the command signals are transferred through a control circuit to the electrical motors which are built in the robot arms and conveyor belt system so that the system reproduces its code and circuit. This work has been done as one of several student projects in a Mechatronics class offered at the Johns Hopkins University. The system presented in this paper has several advantages, one of which is that it is re-programmable. This work may be one of the first steps toward fully autonomous self-replicating robotic factory system.

1 Introduction

The history of self-reproduction or self-replication is quite long, and begins with the history of life on Earth. Every living thing has the power to replicate itself. In nature, nucleic acids, especially DNA, play the core roles in such replications. Consequently, many research studies on understanding and analysis of self-replication systems in biology have been conducted. Motivated by this natural phenomena, self-replication in non-biological things has been studied as well, and works in this category have resulted in the formation of the field of "artificial life"[2]. A representative example of a-life is computer viruses. However, the focus of a-life has been theoretical and algorithmic studies, not constructing real physical systems.

Since the theoretical study of self-replication by von Neumann[1], several researchers have studied on the realization of self replication. For example, Penrose first demonstrated self-reproduction from the mechanical

viewpoint[3]. However, until recently, main research topics have been on the self-assembly or self-reconfigurable robot systems[4, 5, 6, 2, 7].

In the 1970's and early 1980's, NASA conceived of the idea of self-replicating system for space applications[8]. The idea includes the construction of self-replicating factory on the moon. Unfortunately, however, they did not propose any concrete construction of systems. Motivated by this early works, recently, Chirikjian et al. have shown the successful demonstration of an autonomous self replicating robot and possibility of application toward lunar development[9, 10, 11]. On the other hand, in order to realize a true self-replicating system, one needs to develop the system which can replicate its own "brain" from basic parts. That is, true self-replicating system should possess the ability to make a copy of its commands and circuitry to replicate. In this paper, we construct a so-called self-replicating electromechanical intelligence system, which is able to replicate its mechanical code for commands and the electronic circuit to convey the command signal. This work may move us one step further toward fully autonomous self-replication system such as a factory to make use of resources on the moon as construction materials and to make copies of itself.

2 Design and Description of the system

The system was constructed primarily by means of elements in LEGO mindstorm kits. The system presented consists of a robotic system and a conveyor belt system for replicating its code and circuit, and the code and the circuit to be replicated. In Fig. (1) is shown the overview of the system. A conveyor belt feeds the code one line at a time to the reader array. The array then sends the code signal to the control circuit. The signal is decoded as any of seven robot arm or position movements. The robot then carries out the movement command. The commands would tell it to go to one of three feeder positions, pick up the items at that position, move to the assembly line, and drop the items into place. The next set of codes is then fed to the readers, and the process would repeat.

2.1 Mechanical system

Each line of code consists of three bits fed simultaneously to a reader array, which consists of three optical sensors that detect the value of the bits below as black being zero, and white being one. These photo sensor cells are coupled with infrared LED emitters that provide IR light to be sensed by the sensors. IR emitters guarantee the readability of the code even when the ambient light exists. There are seven command signals used out of 23 possible signals. Theoretically, a tactile sensor would detect the position of the source code and move the code appropriately, to the next line of code upon the completion of each movement. The tactile sensor consists of a switch actuated by wooden

bumps placed at the right end of each line of code. This switch would send signals to the control circuit to operate the conveyor belt accordingly. In Fig. (2) is shown the conveyor belt system and the optical reader.

The robot is a two-degree of freedom gantry-style robot, which consists of two arms separated by a constant offset. The designs of each robot arm by LEGO CAD are depicted in Fig. (3) and (4). One degree of freedom is used for positioning along the entire system that includes the feeders and the assembly boards. The other is for the vertical picking-up, perpendicular to the system foundation. Vertical robot arms are used to pick up and drop off code and circuit pieces. The position and arm commands received by the control circuit are carried out and controlled by switches designed and placed to be operated at the completion of each movement. The switches are on the arm itself and these are used to govern the arm height. Another set of switches are along the robot track to govern the robot position. For instance, when lowering the arm to pick up a piece, an obstacle placed at the bottom of the arm trajectory will actuate a switch on the arm. When moving to the assembly boards to drop off the pieces, for example, the robot will hit a switch at the end of the track, signaling the robot to stop.

One of the robot arms picks up the circuit pieces embedded into 2×4 sized LEGO bricks. Each of the three circuit components is picked up at the same location every time, fed by a ramp-type feeder, with blocks sliding down into place by virtue of gravity. Our system is not yet designed to work in gravity-free environments. The other robot arm moves simultaneously and exactly like the first, but with a position offset. This arm picks up the code pieces from an adjacent feeder. This feeder is not a ramp-type feeder but a stack type, with identical code sections simply placed in a stack. This is possible because our code is thin relative to the circuit bricks. The code sections consist of five lines of code, the number necessary to carry out one given set of movements in order to duplicate one circuit piece and code section (i.e. move to feeder, lower, raise, move to assembly board, raise).

The arms pick up the circuit and code pieces by magnetic force. Each arm has a magnet at the manipulator end. Each circuit and code piece has a small piece of ferrous metal embedded in it. The circuit pieces are forced to separate when the arm moves past an obstruction on the assembling circuit board past which the circuit block is too low to move. Similarly, the code sections are forced to separate when the arm moves to the assembly board position, rises to a height at which the code section would encounter an obstruction, and when the arm is sent back to the next feeder, this obstruction prevents the code piece from moving back to the feeder with the arm. By simple separation of the magnets, the circuit blocks and code pieces drop into place onto the assembly boards.

We construct circuit and code on the board, of which the elements are made up of fifteen basic pieces. The code board holds the assembling code sections onto the board through the use of a hook and loop adhesion system, patented by Velcro, USA. The circuit board is pre-wired so that when the

circuit blocks are dropped into place, all of the chip connections are, in theory, instantly made by the contact between copper wire and wire in the chip. Also there are guides on the circuit board to ensure that the chip block has a continuous contact with the circuit board.

2.2 Electrical circuit

The control circuit consists of simple electrical components such as resistors, capacitors, transistors and switches, so that the system is suitable for the simple self-replication. there is no usage of microprocessor in our system. In Fig. (5) is shown the schematic diagram of control circuit. As explained in the diagram, the circuit outlined with dotted line is for replication. We utilize AND, OR, NOT gates in constructing logical circuit. In that diagram, r1, r2, and r3 represent the signals from the optical readers. S1, S2, and S3 represent signals from the feeder position sensors for horizontal movements, and V1, V2, and V3 are those from vertical movements of robot arms. H signal determines the placing position for horizontal movement of the arm. C is from the sensor on the conveyor belt. MH, MV, MC signals drives the electrical motors of robot arms and conveyor belt. Others are internal variables for the communication and feedback of each sub-circuit. For example, q0 and q1 determine whether the conveyor belt should stop or run in accordance with other input signals.

3 Discussions

One of advantages of our system aforementioned is that it is re-programmable. That is, the system preforms various task if we simply change mechanical code and the control circuit accordingly. One possible disadvantage is that, since the system needs 15 codes, each of which consists of 5 lines of 3-bit array, for the completion of one replication, it requires a wide space and consequently longer time. This may be improved if we make use of narrower code array and better-aligned optical readers. We have demonstrated that the system replicates its own code and control circuit. However, we have encountered some problems. The largest one is that, the feedback/state control circuit gave desired signals when separated, whereas it malfunctioned after it was combined with other circuits. Hence, in practice, we utilized modified mechanical code for reading, which does not need tactile sensors on the conveyor belt system. That configuration is shown in Fig. (6). It will be improved if we check more on the circuit analysis. Other problems include the unpredictability of friction between the edge of code elements and the wall, which can be avoided if we change the materials of each component or enhance the alignment of the bridge over which robot is moving, and connectivity of circuit elements with the bottom plate of the circuit replica. Ideally, we would like to design the replica circuit as a plug-in type so that the circuit elements are combined into the circuit board in the same way as combining commercial product called

breadboard with circuit elements such as electronic chips. In that case, we can guarantee the connectivity and also avoid or minimize manufacturing errors, which might lead to the failure of contact between circuit elements and the circuit board.

4 Conclusions

We have presented the prototype of fully autonomous self-replicating electromechanical system which is able to reproduce its own “brain”, i.e., mechanical code and control circuit. The system consists of a robotic system to pick up code and circuit elements and build replicas for mechanical code and circuit, the conveyor belt system to carry the code for reading and code and circuit to be replicated, and its mechanical code and control circuit. By IR emitters and optical sensors, the system can read the command signal from the mechanical code, and transfer those signals via control circuit to robotic system and conveyor belt system to perform the replication of its code and circuit. As a result, the system can adjust various tasks simply by changing corresponding code and circuit. This work may be the initial step toward the realization of self-replicating system, for example, for space applications, such as building a self-replicating factory on the moon to precede a manned base.

5 Acknowledgements

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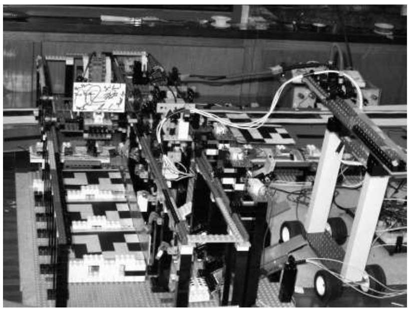

Fig. 1. Overview of the system

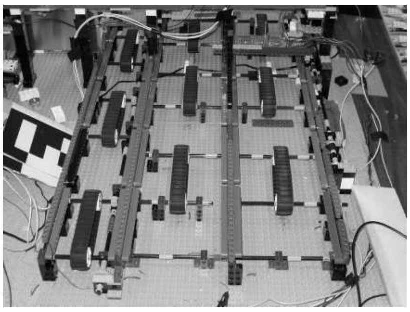

Fig. 2. The view of conveyor belt system and reader

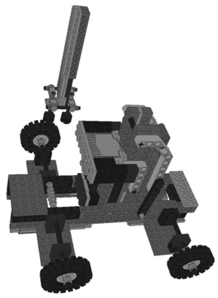

Fig. 3. LEGO CAD of robot arm for picking up the circuit elements

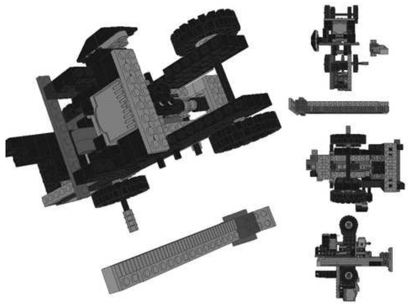

Fig. 4. LEGO CAD of robot arm for picking up the code elements

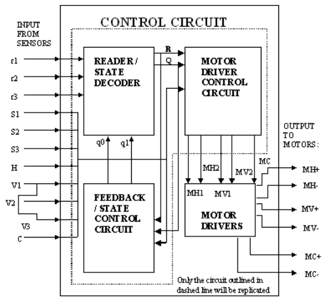

Fig. 5. Control circuit diagram

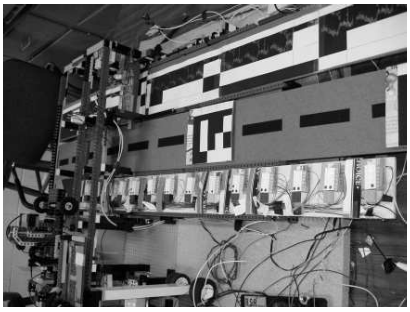

Fig. 6. The example of codes and circuit in demonstration

Toward Self-Replication of Robot Control Circuitry by Self-Inspection

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Extended Abstract

The concept of man-made self-replicating machines was first proposed by John von Neumann, more than fifty years ago [1], and this led to a flurry of related works [2,3]. However, there has never been a physical implementation of his universal constructor architecture in a robotic system. In contrast there have been a number of implementations of self-assembling mechanical systems [4,5]. Prior to our other recent work (see [6]), an autonomous self-replicating mechanical system had not been developed. In contrast to passive self-assembly, a self-replicating system actively utilizes an original unit to assemble a copy of itself from a collection of passive components. However, this does not require the use of von Neumann's universal constructor architecture. In the present work, we demonstrate a non-von-Neumann architecture for the replication of a transistor circuit by active self-inspection. That is, there are no instructions stored about how to construct the circuit, but information observed about the spatial organization of the original circuit is fed into the circuit itself to provide assembly commands. The circuit then drives a larger electromechanical (robotic) system in which it is embedded to cause the production of a replica of the original circuit. In the work presented here, only replication of the control circuit is of interest. In the current context, the electromechanical hardware is viewed as a tool which is manipulated by the control circuit for its own reproduction (much in the same way that deer living in a forest can reproduce without an associated reproduction of the forest itself). This architectural paradigm is demonstrated with prototypes that are reviewed here and compared with an implementation of the universal constructor concept.

This work complements our recent work in which we have demonstrated various aspects of robotic self-replication with a series of prototypes including: (1) remote-controlled systems capable of assembling copies of an original robot from subsystems [7]; (2) a semi-autonomous system in which a remote-controlled robot builds fixtures which then autonomously assist in assembling a copy of the original robot [8]; (3) an autonomous self-replicating mechanical system (in which the computer program for the replica is pre-installed) which functions without human intervention [6]. The present work differs substantially from those works because it focuses on the replication of the ``brains'' of simple robotic systems from individual transistors rather than treating the microprocessor as a preconstructed subsystem in the assembly process.

Over the years the concept of self-replicating robotic systems has been considered to be useful in many applications, especially, space applications. Many researchers have discussed the possibilities of using such a system in space and planetary exploration [9,10,11]. In order to make this vision realistic, one must show that self-replication of intelligence (SRI) is possible. We believe that the non-von-Neumann concept of self-replication by self-inspection, first addressed theoretically by Burks [13], Arbib [12], and Liang [14] (and implemented in electromechanical systems for the first time here) is a paradigm which is very robust and worthy of consideration.

The SRI concept: Ideally, for a robotic system to be truly self-replicating, it would have to demonstrate the ability to assemble all of its own subsystems from the most fundamental components. In the case of the robot controller, we consider the most fundamental components to be transistors, resistors, capacitors, etc., whereas microcontrollers are too complex to be considered as basic elements.

Our approach is to build a circuit capable of controlling an electro-mechanical system to re-build replicas of the control circuit from the most fundamental electronic components. In the von Neumann universal constructor paradigm, an associated instruction code is also required. In contrast it is possible to replicate a particular system by self-inspection without invoking von Neumann's universal constructor. We illustrate both concepts in hardware designed and constructed by students in a Mechatronics course taught at Johns Hopkins University in 2003. Two prototypes illustrate replication by self-inspection, and one demonstrates the universal constructor. In all three cases, pre-built electro-mechanical systems (called the SRI-builders) use the transistorized circuit as its controller. While in the von Neumann paradigm, the controller follows instructions that are explicitly encoded (and hence must reproduce the code for the overall system to be self-replicating), in the self-inspection paradigm, actions are taken implicitly as a result of observing the spatial layout of components in the original and feeding that information into the circuit itself. Clever electromechanical design ensures that observations obtained during self-inspection are translated directly into actions without requiring the interpretive step of consulting a long sequence of encoded construction commands.

(1) A von Neumann Universal Constructor Prototype: The robotic system is a two-degree of freedom gantry-style robot, consisting of two arms separated by a constant offset. One degree of freedom is the position along the entire system that includes the feeders and the assembly boards. The other is the vertical direction, perpendicular to the system foundation, used by the arm to pick up and drop off code and circuit pieces. The position and arm commands received by the control circuit are carried out and controlled by switches designed and placed to be operated at the completion of each movement. There are two boards being assembled at any given time, one for the circuit and one for the code. The circuit board is pre-wired so that when the circuit blocks are dropped into place, all of the chip connections are, in theory, instantly made. Each line of code consists of three bits fed simultaneously to a reader array consisting of three optical sensors that detect the value of the bits below – black being zero, white being one. These photo sensor cells are coupled with infrared LED emitters that provide IR light to be sensed by the sensors; ambient visible light has the potential of providing sufficient light energy to reflect off the code and be detected by the sensors, but the IR emitters guarantee the readability of the code. See Figure 1.

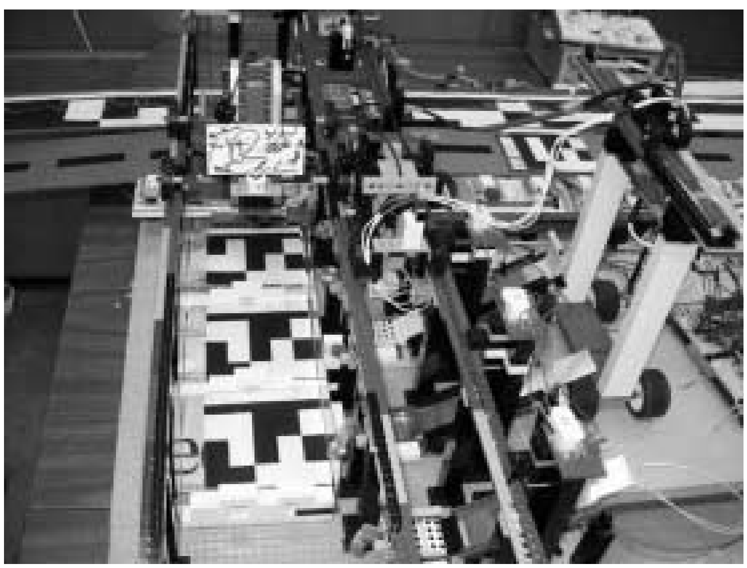

Figure 1: Side View of the Replicating system

(2) Non-universal self-replication by self-inspection (design 1): This self-replicating control circuit has the ability to identify the proper electronic components required, translate information about its own constituent parts obtained from self-inspection into mechanical tasks that create a replica , and transfer all functions to the replica. There is no list of instructions in the form of a code. Each electronic component has a black-and-white color code. Parts are loaded into feeders, and as a reading head traverses the control circuit, the information about which part of the control circuit is being observed is fed into the circuit itself. This actuates the solenoid in the appropriate feeder to release the parts needed to form the replica. Parts then slide

down an incline and form an orderly array. The reading head continues to move and creates replicas until resources are completely utilized or its track ends. The design is scalable and the components are modular, allowing many different levels of intelligence to be replicated. This concept is one of many which we are investigating to enable self-replicating robots to perform complex behaviors. See Figure 2.

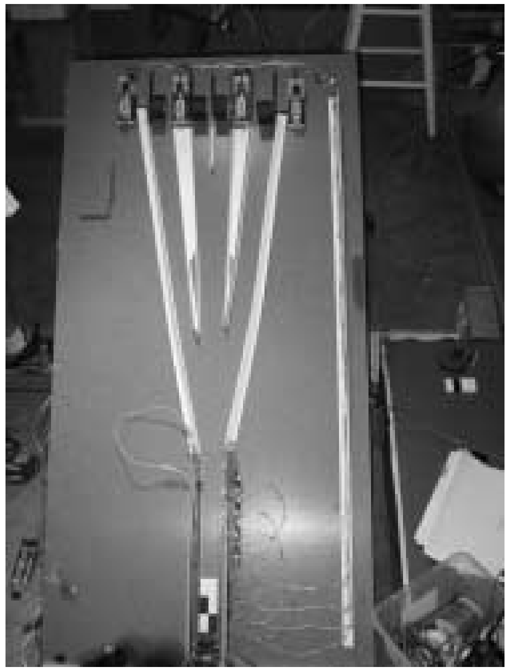

Figure 2: Side View of the Replicating system

(3) **Non-universal self-replication by self-inspection (design 2):** This robotic system is an X-Y table constructed from modified LEGO components. A photo-transistor sensor system is attached to the end-effector of the X-Y system in order to inspect the control circuit (the components of which are each assigned a unique black and white code). On the top of the X-Y system, a set of component feeders is installed. The circuit converts the signal from the sensor system to control the component feeders to release the correct component to the parts assembler. The parts assembler then arranges all the components to create a new replica of the control circuit. See Figure 3.

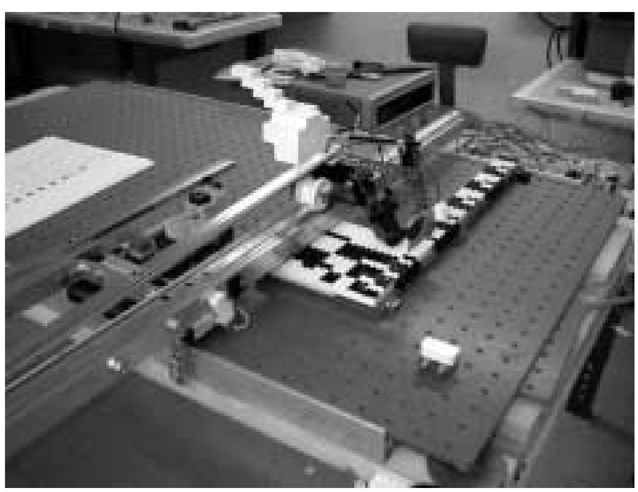

Figure 3: Side View of the Replicating system

Discussion

Whereas von Neumann's architecture for self-replicating kinematic automata is the most widely known approach, it is not the only one. Self-reproduction by self-inspection in which a non-universal constructor `reads' an original device and `writes' a copy by executing a very small set of hardwired commands is an alternative. In our experience observing students attempting to build self-replicating devices, self-replication by self-inspection appears to be a more robust and less complicated alternative to the universal constructor.

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