# 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 behaviors. 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 behaviors, which is an initial step in the direction of self-replicating robots.*

## 1 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 channeled 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.

## 2 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 consisting 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).

### 2.1 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.

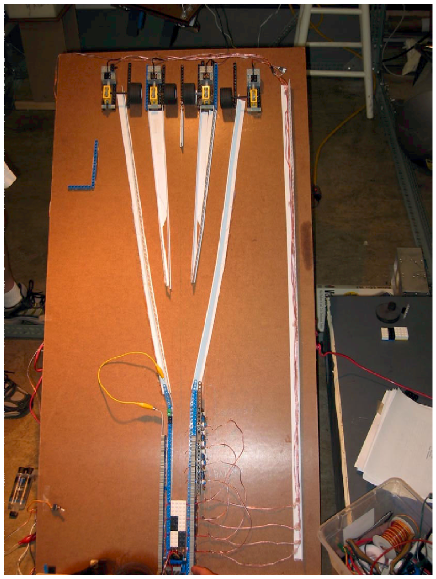


**Figure 1.** Overview of the Manipulation System on which the Self-Replicating Circuit Acts.

An overview of the mechanical design is shown in Figure 1.

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.

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.

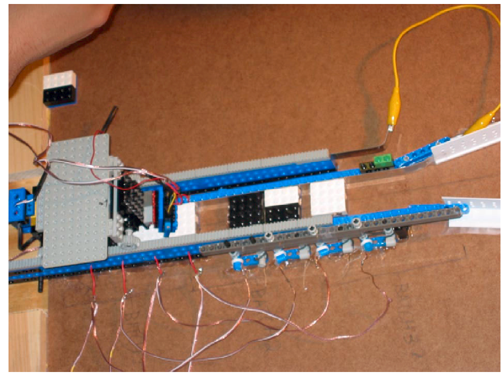


**Figure 2.** View of the Reader, Modules and electrical connections

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.

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

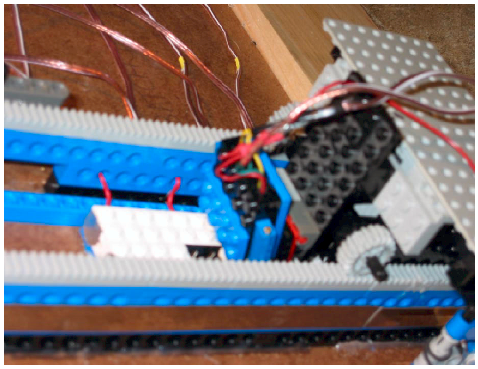


**Figure 3.** View of the reader and light sensors

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.

### 2.2 Circuit design

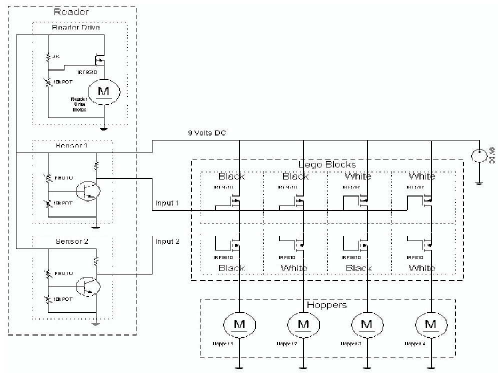
The control circuit must be able to read a code that will control the mechanical element of the robot for retrieving and delivering the circuit components for our replica. In this case, the reader must send a voltage signal to the four-module circuit within the LEGO blocks, which in turn activates the 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).

## 3 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 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



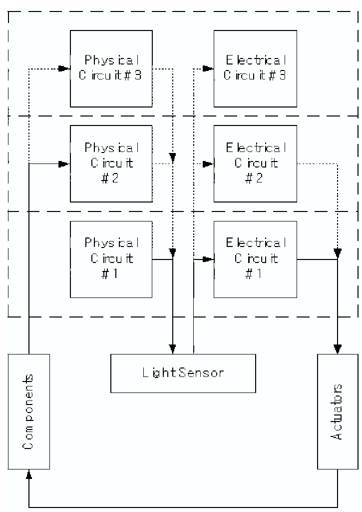




**Figure 4.** View Schematic of Self-Replicating System. Note that the circuit acts as a physical encoder of black and white colors and as an electrical circuit.

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.

## 4 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.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