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

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Abstract. The concept of man-made self-replicating machines was first proposed by John von Neumann more than 50 years ago. However, there has never been a physical implementation of his universal constructor architecture as a robotic system. Prior to our other recent work, an autonomous self-replicating mechanical system had not been developed. In this paper, we demonstrate a non-von-Neumann architecture for the replication of transistor circuits 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 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. This architectural paradigm is demonstrated with prototypes that are reviewed here and compared with an implementation of the universal constructor concept.

1 Introduction

1.1 Motivation

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

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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.

1.2 Related Works

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 ofself-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.

In the next section, our approach to self-replicating intelligence is described. Section 3 describes demonstrations developed by our students and their results, and Section 4 presents our discussions.

2 Our Approach on Self-Replicating Control Circuitry

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.

3 Experiments and Results

3.1 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

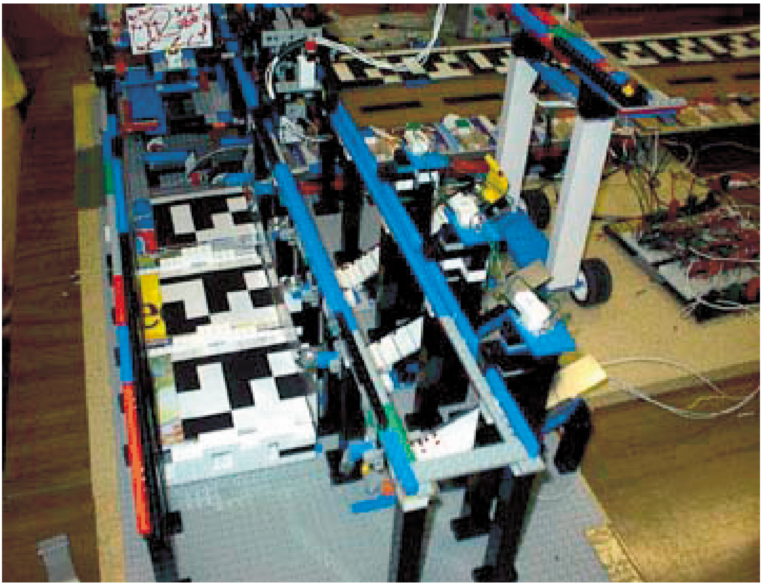

Fig. 1 Side View of the Replicating system (Von Neumann Universal Constructor Prototype.)

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.

3.2 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.

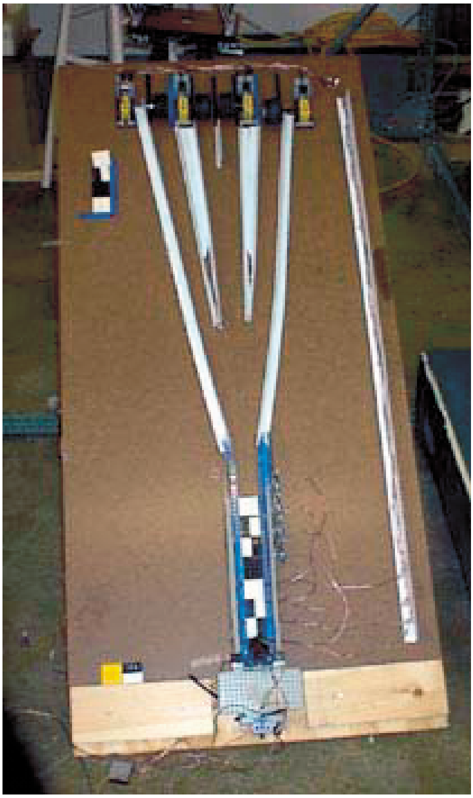

Fig. 2 Side View of the Replicating system (Non-Universal Self-Replication by Self-Inspection – Design 1.)

3.3 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.

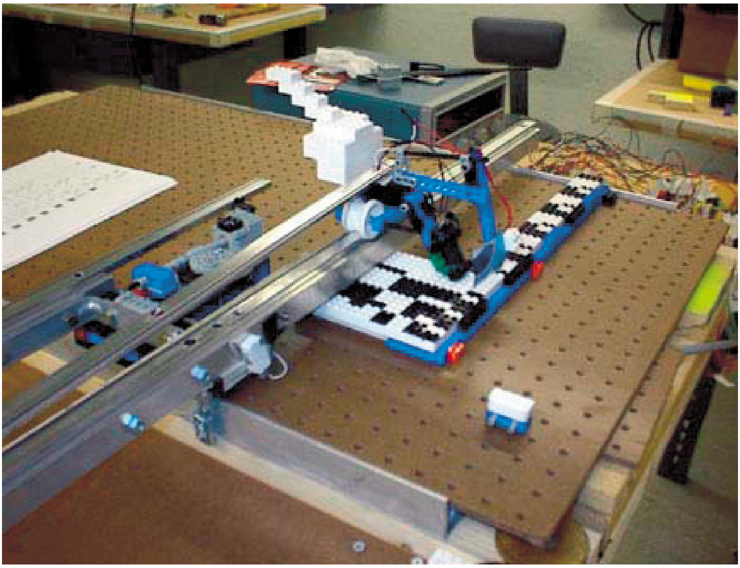

Fig. 3 Side View of the Replicating system (Non-Universal Self-Replication by Self-Inspection – Design 2.)

4 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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