Robotic Self-replication in Structured and Adaptable Environments

Kiju Lee, Matt Moses and Gregory S. Chirikjian
Department of Mechanical Engineering, Johns Hopkins University
Baltimore, Maryland 21218

Since the first theoretical work on self-replicating machines was performed by John Von Neumann [1], his ideas have been applied in many research areas such as cellular automata, nanotechnology, macromolecular chemistry and computer viruses [2]. Penrose, in [3], presented simple units with certain properties able to self-replicate. Although his work could not make the further step toward self-replicating robotic systems, he opened the possibility of mechanical implementation of Neumann's concept. More recent studies include self-assembly ([4],[5]) and self-reconfiguration of modular robots and self-repairable robots([6],[7]). In addition, self-replicating modular cubes are presented in [8].

Our lab has built several prototypes to improve and demonstrate the concept of robotic self-replication. Remote-controlled, semi-autonomous and fully-autonomous self-replicating robots have been developed over the past few years ([9]-[11]). In addition, self-replicating, electromechanical circuits were demonstrated [12]. The circuits used electromechanical devices as substrates in order to construct functional copies of themselves.

In this paper, we extend and combine our previous results in that the control circuits of the robot are distributed into a number of subsystems rather than having an integrated controller. In order to prove our idea of robotic self replication, the following criteria must be met.

- The robot consists of several prefabricated subsystems.
- The subsystems are not identical and each of them is incomplete by itself.
- The replica becomes fully functioning only when it is completely assembled.
- The subsystems have similar structural complexities.

The second and third criteria clarify the distinction between our robot and other self-replicating modular robots. To satisfy the fourth criterion, we *distributed* the electrical circuit into a number of subsystems.

We present three prototypes of self-replicating robotic systems:(**Robot I**) a finite-state self-replicating robot in a *partially* structured environment in which subsystem locations can be permutated, (**Robot II**) an autonomous self-replicating robot in a *completely* structured environment and (**Robot III**) an autonomous self-replicating robot in an emphadaptable environment in which the robot modifies its surroundings after certain tasks have been completed. These prototypes use the line-tracking thereby reducing the environment to a 1-dimensional domain.

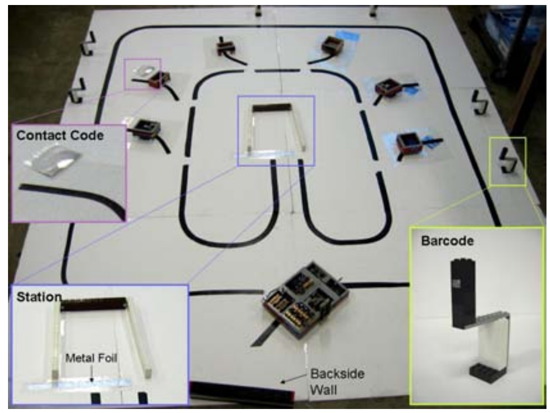

Fig. 1. Robot I in a structured environment

Robot I consists of six subsystems: Module1(batteries, touch sensor and contact sensors), Module2(state machine and contact sensors), Module3(left motor and motor driver circuit), Module4(right motor and barcode reader), Module5(relay circuit) and Module6(tracker sensor). The state machine has six states and the robot has three distinctive behaviors for each state: forward line-tracking, reversing and left turning while the timer is on. These are decided by outputs from two different kinds of sensors, barcode reader and contact sensors. The environment is built as shown in Fig.1. The environmental structures are divided into two categories: (1)passive structures and (2)active structures. The active structures store the information about subsystems, therefore, the environment tells the robot where subsystems are and what they are. On the other hand, passive structures affect the trajectories of the robot but do not have further information.

There are 6! ways in total to locate subsystems. Passive structures are fixed once they are built and active structures are placed according to the location of each subsystem. The robot starts from the outer track and turns left once it finds the right barcode so that the state machine triggers the timer. Between the outer and the inner tracks, the robot picks up a subsystem and the state is transitioned to the next. The robot drags the part until it detects metal foil at the station, reveres until it hits the wall, and goes back to the outer track to find the next subsystem.

Robot II in a completely structured environment is shown in Fig.2. The functions of the robot are limited to line-tracking and reversing direction. The environment includes

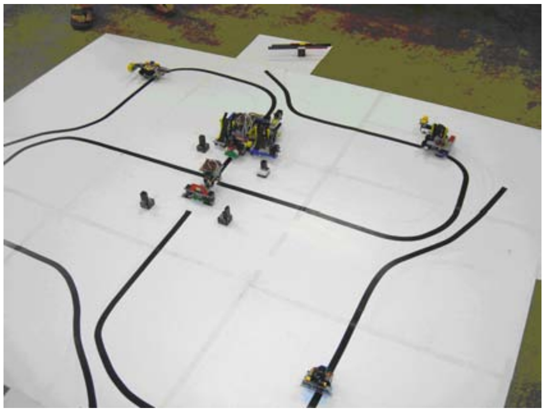

Fig. 2. Robot II in a completely structured environment

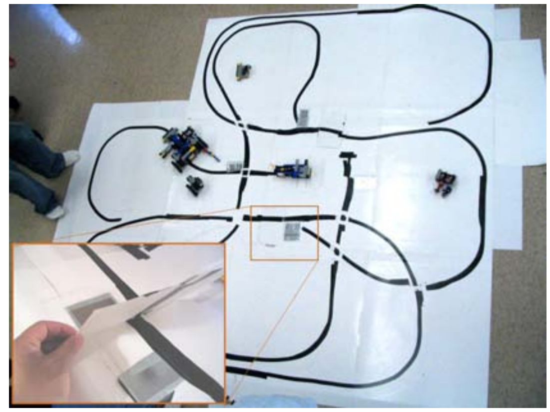

Fig. 3. Robot III: in adaptive environment with flipping cards

black-colored track on a white surface, poles around the central station (where the replica will be assembled) and walls outside the track. These structures lead the robot to move along the desired trajectories. The robot consists of five subsystems: central part, left wheel, right wheel, magnetic end-effector and rear battery pack. The central part must be placed at the station. According to the orientation of the central part, the locations of the other subsystems are determined. While the robot follows the track, if it sees a subsystem, the magnetic end-effector automatically picks up the part and drags it to the station. The robot has two defined behaviors which are (a) moving foreword and along the line (line tracking mode: mode 1), and (b) moving backward blindly (reversing mode: mode 2). There are two events which trigger a change in state. A triggering of the frontal touch sensor causes the robot to transition from mode 1 to mode 2. A triggering of the rear touch sensor causes the robot to transition from mode 2 to mode 1.

Robot III is built in an *adaptable* environment is shown in Fig.3. The robot consists of six distinct modules: base/chassis, motor module, battery pack, line tracking module, electromagnet, and electromagnet control module. The end-effector consists of an electro-magnet. The state of the end-effector is ON while the robot follows the track, and OFF when the robot detects one of five patches of metal foil on the surface of the floor. Therefore, the end-effector can pick the parts and place them at the right locations if the metal foil is located where the subsystems are to be released. A unique feature of the environmental design for this robot is its adaptability. The bi-state mechanical "flip-flop" (a card that gets flipped the first time the robot passes over it) makes the robot be able to change and modify the environment during the replication process. The flip-flop cards reveals a new foil contact/drop point while changing the track to initialize the second pass on the same side of the chassis. This simple technique works very effectively and consistently, although, as it stands, human intervention is required to reset the cards after each successful demonstration of self-replication.

We has been developing several prototypes of self-replicating robots in structured and adaptable environments. In order to make a further step from the current work, we need to consider the following questions: How can we store necessary information in the environment effectively? How can the environment transmit the information to the robot with minimum loss and errors? How can self-replicating robots perform in less structured environments?

ACKNOWLEDGMENT

We thank to Steven Eno, Jianyi Liu, Lauren Mace, Brian Benson, Kailash Raman, Andrew Liu, Matt Sterling, Diana Kim, Andrew Pierpont and Aaron Schlothauer who developed Robot II and Robot III as part of our Spring'06 Mechatronics course.

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