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Robotic Self-Replication

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Abstract

The concept of an artificial corporeal machine that can reproduce has attracted the attention of researchers from various fields over the past century. Some have approached the topic with a desire to understand biological life and develop artificial versions; others have examined it as a potentially practical way to use material resources from the moon and Mars to bootstrap the exploration and colonization of the solar system. This review considers both bodies of literature, with an emphasis on the underlying principles required to make self-replicating robotic systems from raw materials a reality. We then illustrate these principles with machines from our laboratory and others and discuss how advances in new manufacturing processes such as 3-D printing can have a synergistic effect in advancing the development of such systems.

1. INTRODUCTION

For more than a century, the idea of a machine that can reproduce itself under automatic control has been a source of fascination (1). Many pioneering mathematicians, scientists, and engineers contributed to early work in this area, including John von Neumann (2), Arthur W. Burks (2), Edward F. Moore (3), Lionel and Roger Penrose (4), Konrad Zuse (5), and Freeman Dyson (6). By all accounts, machine self-reproduction is a difficult and currently unsolved problem (see, e.g., 7–11).

To the best of our knowledge, there are currently no examples of a robotic or other artificial system that completely self-reproduces in a manner equivalent to a biological organism. There are, however, several experimental (and in some cases industrial) systems that exhibit some aspects of self-reproducibility. Many of these examples overlap with related fields, such as biologically inspired robotics (9), evolutionary robotics (12), modular reconfigurable robotics (10), self-assembling robots (13, 14), robotic construction (15), low-cost 3-D printing (16), and even artificial life (17). This review presents examples from these many overlapping fields, including demonstrations of new technology that could be used in future self-reproducing systems, even if they were not explicitly developed for that purpose. The emphasis is on work that has appeared since the last major review on self-replicating machines was published in 2004 (8). In addition, since the boundaries between robotics, materials, and chemistry are becoming ever more blurred (see, e.g., 18–20), the review includes some relevant work with artificial self-reproduction in chemistry and biochemistry.

2. THE FOUNDATIONAL WORK OF VON NEUMANN

An author writing today would not begin a review of modern computers by going all the way back to the early writings of computing pioneers. However, because the technology of self-reproducing machines remains, by comparison, quite underdeveloped, it is instructive and helpful to begin at the beginning. Modern work in self-reproducing machines is always traced back to John von Neumann, who first presented his ideas on the topic as a series of lectures in the late 1940s. After his early death in 1957, his notes and lectures on self-reproducing machines were completed and compiled into book form by Arthur Burks (2). As explained by Burks, von Neumann

> envisaged a systematic theory which would be mathematical and logical in form and which would contribute in an essential way to our understanding of natural systems (natural automata) as well as to our understanding of both analog and digital computers (artificial automata). (2, p. xv)

Von Neumann's work did indeed contribute in an essential way, and his influence is seen in much of even the most recent work discussed in this review. Of the many ideas he and Burks presented, we briefly highlight three: the kinematic model, the logical model, and the cellular model.

2.1. The Kinematic Model

In an attempt to describe how constructing robots could have "outputs something like themselves" (2, p. 75), von Neumann suggested the following:

> Draw up a list of unambiguously defined elementary parts. Imagine that there is a practically unlimited supply of these parts floating around in a large container. One can then imagine an automaton functioning in the following manner: It also is floating around in this medium; its essential activity is to pick up parts and put them together. (2, p. 75)

On the one hand, the influence (or at least prescience) of this idea is seen in modern studies where the robotic components are literally floating or submerged in fluid (21–24) or are placed on a surface and can be accessed by mobile robots (13, 25). On the other hand, von Neumann was the first to admit the limitations of his abstract model:

> By axiomatizing automata in this manner, one has thrown half of the problem out the window, and it may be the more important half. One has resigned oneself not to explain how these parts are made up of real things. (2, p. 77)

The problem of creating such axiomatic parts out of "real things" consumes a great deal of effort in modern self-replicating robot work.

2.2. The Logical Model

Von Neumann's logical model is probably the most widely known and highly cited aspect of his work on self-reproduction, because the simplicity and generality of it make it applicable to a wide range of systems. The model assumes a universal constructing machine A, composed of the above-mentioned "unambiguously defined elementary parts," that can construct other machines from similar parts using a suitable description. Instructions for constructing a general machine X can be encoded in an information storage medium (often colloquially referred to as a punched tape) represented as $\phi(X)$. The action of the constructing machine A is represented as

$$A + \phi(X) \rightarrow A + X. \tag{1}$$

A copying machine B simply copies the punched-tape representation,

$$B + \phi(X) \rightarrow B + \phi(X) + \phi(X); \tag{2}$$

a controller C coordinates the actions of A and B so that they can work together to copy and then interpret the punched tape,

$$(A + B + C) + \phi(X) \rightarrow (A + B + C) + X + \phi(X); \tag{3}$$

and, finally, the combined system $(A + B + C)$, when presented with instructions $\phi(A + B + C)$, will self-replicate:

$$(A + B + C) + \phi(A + B + C) \rightarrow (A + B + C) + (A + B + C) + \phi(A + B + C). \tag{4}$$

This model has been applied to many different problems and has been extended by many researchers for a wide variety of applications. Some of this work is discussed in greater detail in Section 6.

2.3. The Cellular Model

According to Burks, the mathematician Stanislaw Ulam suggested to von Neumann that

> a cellular framework would be more amenable to logical and mathematical treatment than the framework of the kinematic model. In the cellular model, self-reproduction takes place in an indefinitely large space which is divided into cells, each cell containing the same finite automaton. (2, p. 94)

This collaboration initiated the field of what is today called cellular automata, which are used to model a wide range of complex phenomena, including self-reproduction and evolution (26). Just as there is some similarity between the kinematic model and modern work on mobile or stochastically driven modular robotics, there is a resemblance (more than superficial) between the cellular model and modern robotic modular components that operate in regular grids (e.g., 27–30).

3. MODELING SELF-REPLICATING SYSTEMS AS DIRECTED GRAPHS

In this section, we present a descriptive framework for self-reproducing machines adapted from similar work first introduced (to our knowledge) in 1999 by Hall (31). This framework is helpful for comparing a wide variety of different fully and partially self-reproducing and self-replicating systems. It also serves as a starting point for defining certain performance metrics that can provide relative comparisons of the versatility and usefulness of different systems.

The basic action that self-replication depends on is that of making something. Loosely speaking, in a self-replicating robotic system, things make other things until we end up with a copy of what we started with. This action of making can be represented in a directed graph. In this model, based on concepts presented in References 31–33, each node in the graph can be a member of three sets: resources $r \in R$, manufacturing units $m \in M$, and outcomes $o \in O$. For the purposes of this review, the definitions of R, M, and O are left somewhat vague, allowing the general application of the model. For example, resources can include energy, raw material, and information; manufacturing units can include lathes, enzymes, 3-D printers, robot arms, and human technicians; and outcomes can include processed materials, information, machines, and waste products. These classifications are not mutually exclusive—membership in the various intersections of R, M, and O allows further division into seven possible classifications, as shown in **Figure 1**.

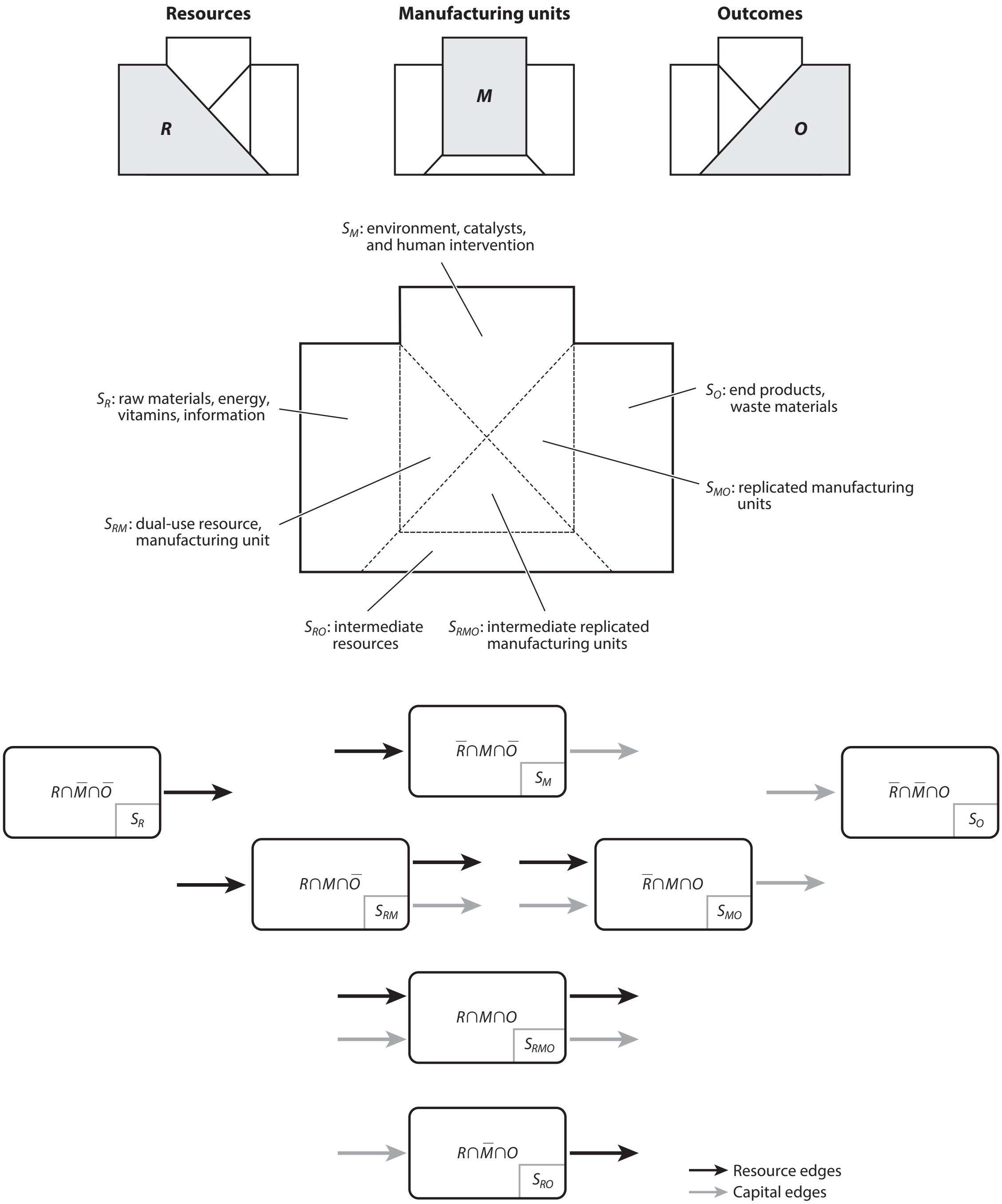
As observed by Hall (31), two types of edges are required: resource edges and capital edges. A resource edge connects a resource r to a manufacturing unit m, and its action in words can be stated as "is used by." A capital edge connects a manufacturing unit m to an outcome o, and its action in words can be stated as "produces." **Figure 2** shows von Neumann's original self-replicating universal constructor represented in graph form. The mnemonic convenience of the resource/capital edge representation can be illustrated by a simple example: "The punched tape *is used by* the controller, the controller *produces* control signals, the control signals *are used by* the constructor, and the constructor *produces* constructors."

A fully self-replicating system, such as the one in **Figure 2**, is one in which every node is the outcome of a manufacturing unit within the network. [In Hall's phrasing, every node is the "terminus of an endogenous capital edge" (31, p. 325).] A partially self-replicating system—such as the replicating rapid prototyper (RepRap) shown later in **Figure 6** (see Section 7)—is one in which only some of the nodes are outcomes of manufacturing units within the network. Depending on the desired application, a partially self-replicating system may be satisfactory. In addition to the full/partial distinction, the performance of a network can be quantified (at least to a certain extent) by applying complexity measures (33–35) to the resources and outcomes (or more generally to each node in the system) and then computing the ratio of the complexity of outcomes to that of the necessary resources. Complexity measures are discussed in greater detail in Section 6.

4. MOTIVATION AND APPLICATIONS

4.1. Space-Based Mining and Manufacturing

The idea of using self-replicating spacecraft to assist with the colonization of space and utilization of extraterrestrial resources has a long history in science fiction. According to Freitas & Merkle (8), the first appearance of this idea in scientific literature was in a book chapter by Arbib (36) published in 1974. Freeman Dyson considered the idea in his 1979 book *Disturbing the Universe*



(Caption appears on following page)

Figure 1 (*Figure appears on preceding page*)

A manufacturing system modeled as a directed graph, where nodes represent resources R, manufacturing units M, and outcomes O (31–33). As shown in the Venn diagram, nodes may be members of more than one set. For example, a robot arm can be both an outcome and a manufacturing unit, and in shorthand notation, the set it belongs to would be denoted S_{MO}. A graph edge represents a transformation where a resource R is transformed into an outcome O by a manufacturing unit M. Two types of edges are required: resource edges (*black arrows*) connect resources to manufacturing units, and capital edges (*gray arrows*) connect manufacturing units to outcomes.

(6). The first in-depth engineering study was performed as part of a 1980 NASA Summer Study, with the results edited by Freitas & Gilbreath (37). The study's authors proposed to design a factory as an

> automated, multiproduct, remotely controlled, reprogrammable Lunar Manufacturing Facility (LMF) capable of constructing duplicates of itself which would themselves be capable of further replication. Successive new systems need not be exact copies of the original, but could, by remote design and control, be improved, reorganized, or enlarged so as to reflect changing human requirements. (37, p. 189)

The 1980 NASA study stopped short of performing detailed design. A handful of other studies have been performed since 1980, but none at the level of a major project. A common theme and motivation in all of these studies is that self-replication enables the amplification of manufacturing power: A small seed sent into space can grow into a powerful system, avoiding the tremendous costs associated with getting materials into space.

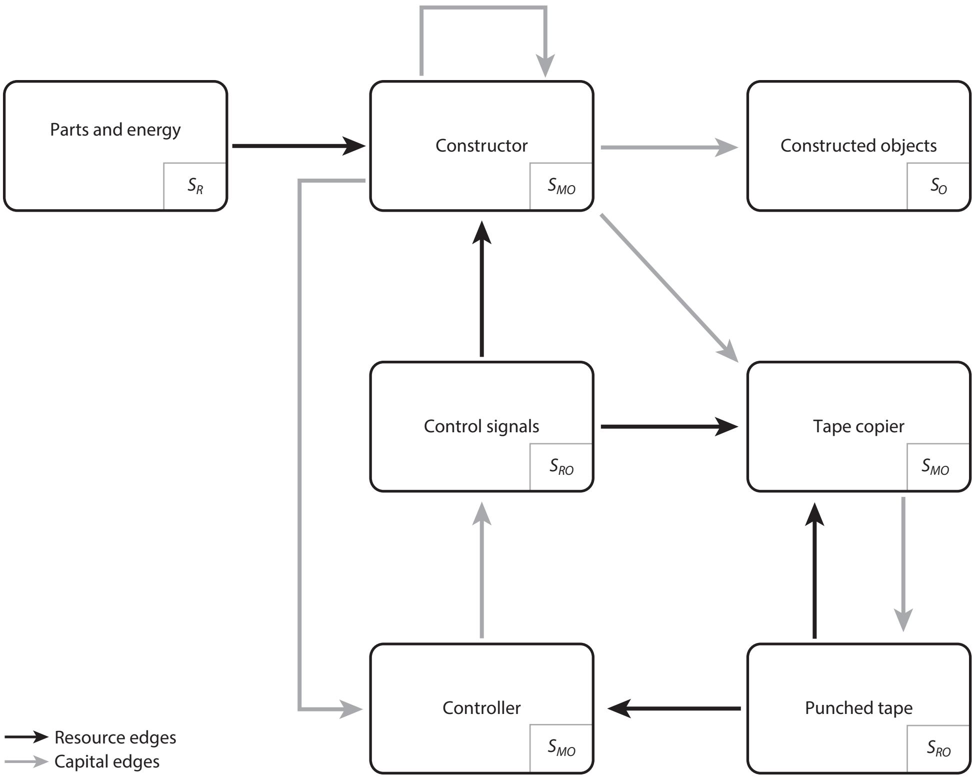


Figure 2

Graph network representation of a von Neumann self-reproducing universal constructor. Black arrows represent resource edges, and gray arrows represent capital edges. Figure adapted from Reference 31.

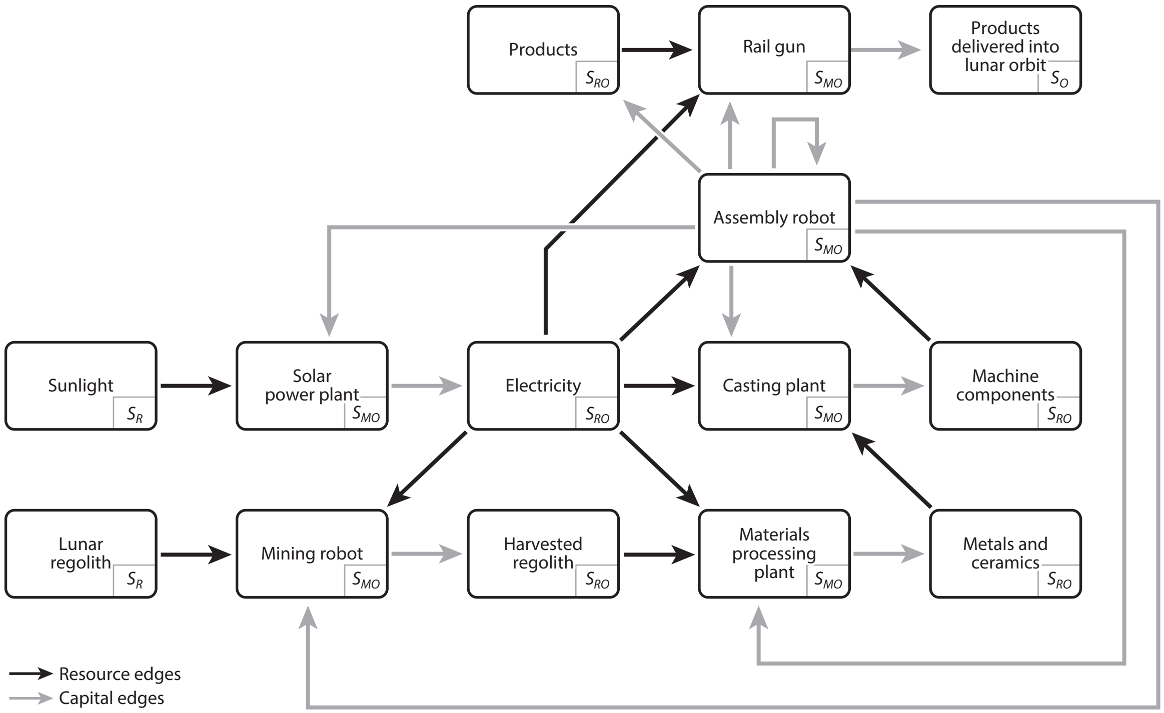


Figure 3

An architecture for a self-replicating lunar factory. Black arrows represent resource edges, and gray arrows represent capital edges. Rail guns can be one of any number of electromagnetic launch technologies, and casting is one of a number of parts manufacturing technologies. Goods transported to lunar orbit and beyond can be used to bootstrap space manufacturing and colonization throughout the solar system. Figure adapted from Reference 39.

From 2002 to 2004, Chirikjian and colleagues (38, 39) developed an architecture for a self-replicating lunar factory. The proposed architecture, shown in **Figure 3**, consists of five subsystems: (*a*) multifunctional robots for the digging and transportation of materials and the assembly of components during the replication process; (*b*) a materials-refining plant; (*c*) a parts-manufacturing facility; (*d*) a power plant for solar energy conversion, storage, and transmission; and (*e*) electromagnetic rail guns for the long-distance transportation of finished products and additional replicated factory seeds. Numerous proof-of-principle demonstrations of self-replicating robots were carried out, in addition to the identification of candidate manufacturing methods and materials as well as control strategies using minimal computer designs.

The development of lunar resources has the potential to greatly enhance humanity's ability to explore and colonize space. If significant portions of the moon can be used for solar energy collection, and its regolith can be effectively collected and processed into refined materials and machines, then the resulting energy and refined material products can be stockpiled for later use by human colonists and eventually transported to Earth orbit or elsewhere in the solar system (see **Figure 4**).

In 2013, Metzger et al. (40) proposed a bootstrapping seed factory for lunar development. Manion et al. (41) presented a design and simulation of a self-replicating robotic manufacturing factory in space based on a multiagent system design. Langford et al. (30) developed an ingenious set of 13 types of small modular robotic components that could potentially build a self-replicating

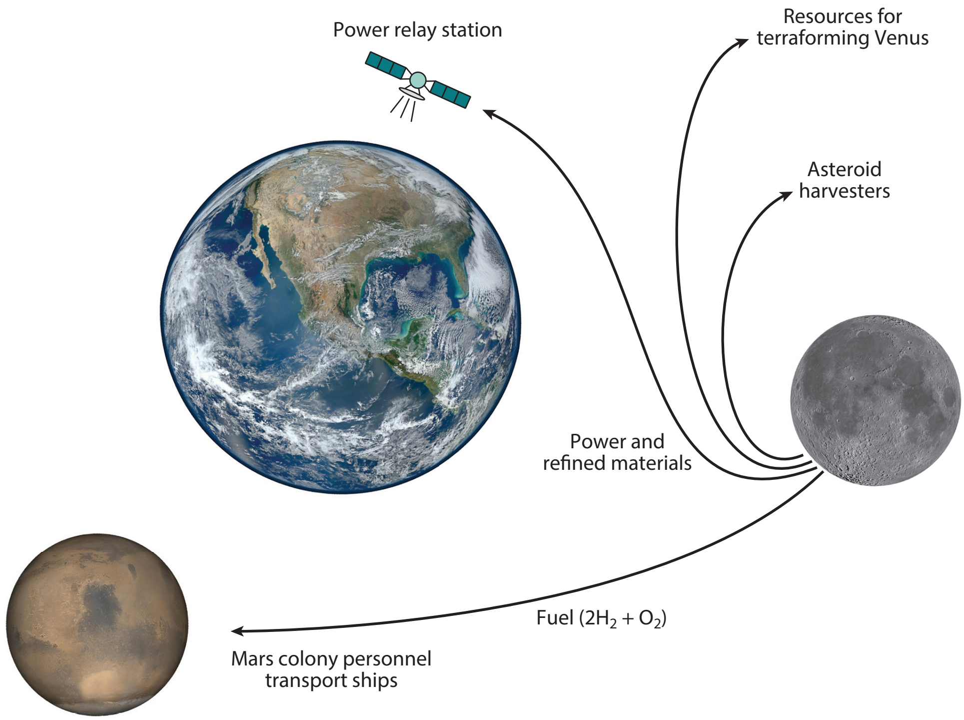


Figure 4

The impact of self-replicating lunar factories on the utilization of space. Earth image by NASA/NOAA/GSFC/Suomi NPP/VIIRS/Norman Kuring; moon image by NASA/GSFC/Arizona State University; Mars image by NASA/JPL/MSSS.

constructor small enough to fit within the envelope of a CubeSat. Most recently, Ellery (42, 43) proposed a 3-D-printing-based system architecture for a lunar factory and presented several proof-of-principle demonstrations of prototype motors, circuits, vacuum tubes, and a "low-cost Fresnel lens-powered multi-material 3D printer" (43, p. 380).

4.2. Large-Scale Manufacturing on Earth

In 1995, physicists Klaus Lackner and Christopher Wendt proposed building large industrial installations using self-replicating machines and described some of these machines' unique potential advantages:

> In principle, self-reproducing machines would offer a new and different means for society to accomplish very large scale tasks, which include those currently achieved by great repetition of design and/or building effort, as well as those currently unimaginable because of their scale. Examples are collection of solar energy, direct removal of greenhouse gases from the Earth's atmosphere, and desalination of water for irrigation. The special feature of the self-reproducing machine approach is that effort is focused on design and construction of a small seed system, and the large scale follows from exponential growth of this system through a few tens of generations. (44, p. 56)

In the decades since 1995, self-replicating machine tools have made a noticeable impact in the area of low-cost 3-D printing (45,46). As described by Laplume et al. (47, p. 633), when 3D printing was made open source with RepRaps, resultant competition and innovation pushed prices down of the printers to within reach of consumers. RepRaps can manufacture over 50% of their own components (excluding fasteners) creating a low cost, easily repairable and upgradeable 3D printer that can be used for fabrication of complex parts and products at costs that are a fraction of commercially available alternatives.

The "easily upgradable" feature of properly designed self-reproducing machines suggests a number of applications that go beyond basic manufacturing, as discussed in the next section.

4.3. Bootstrapping and Open-Ended Machine Evolution

The ability to evolve new capabilities is an additional advantage that self-replicating machines can offer over the basic property of amplification of manufacturing power via growth. Naturally, human technology as a whole has replicated and increased in complexity over time. But, much like biological evolution, on a large scale, the evolution of human technology has been undirected, ad hoc, and (obviously) reliant on having humans in the loop.

It is interesting to consider the possibility of self-contained machine systems that possess their own ability to evolve. Von Neumann included just such a possibility in his logical model of self-replication: The instructions for producing the system $(A + B + C)$ are augmented with instructions for an additional feature D that provides some new capability. This improvement can then be reproduced and carried forward into future generations:

$$(A + B + C) + \phi(A + B + C + D) \rightarrow (A + B + C) + (A + B + C + D) + \phi(A + B + C + D). \quad 5.$$

Figure 5 shows a graph representation of this process, indicated as the bootstrapping route. [In this context, the term bootstrapping is used to indicate a process that automatically increases in complexity (31, 37, 40).] It depicts three different routes to obtaining an end product: a direct route, a bootstrapping route, and bootstrapping augmented with "vitamins" (i.e., special-purpose

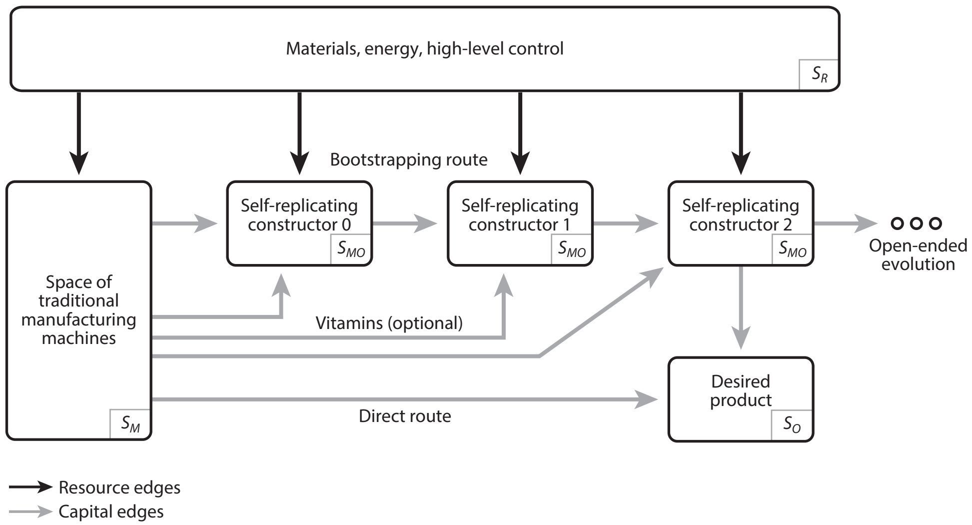


Figure 5

Comparison of three routes to obtaining an end product: a direct route using only traditional manufacturing machines, a bootstrapping route via self-replicating intermediates, and bootstrapping augmented with optional "vitamins" (special-purpose components that cannot be replicated).

components that cannot be replicated). For typical applications, the direct route is optimal—there is no need to insist on using self-replicating manufacturing tools in ordinary circumstances. There are, however, several scenarios where bootstrapping becomes advantageous or even necessary.

Bootstrapping routes can lower costs and increase the availability of specialized equipment. For example, a well-known series of books by Gingery (e.g., 48) describes how to use augmented human-in-the-loop bootstrapping to build a set of functional machine tools from scrap metal and simple parts. Similarly, Pearce (49) has advocated using low-cost 3-D printers to build scientific instruments.

Bootstrapping could help create manufacturing tools that are presently impossible. One well-known example, suggested by the physicist Richard Feynman in 1959 (after being inspired by Robert A. Heinlein's science fiction story "Waldo"), is the possibility of using recursively smaller and smaller self-reproducing factories as a route to ultimately building machines that could directly manipulate atoms (50, 51). Bootstrapping of industrial facilities has been proposed for space manufacturing and colonization (38, 40, 43).

There is also motivation to study nonaugmented pure-bootstrapping sequences of self-replicating machines that can potentially demonstrate open-ended evolution. The reason to pursue open-ended evolution in self-replicating robots parallels that for pursuing evolutionary robotics in general: The process itself is of scientific interest (52). Just as artificial chemistries (see Section 6.2) are used to study aspects of complex phenomena that are difficult to obtain in other models or real chemistries, open-ended machine evolution could serve as a practical tool to elucidate aspects of evolution that might be difficult to study in biological or simulated systems. Additionally, the evolutionary process may produce surprising solutions to engineering problems that humans could not have discovered (12, 20, 53, 54).

Pioneering work in robot evolution used computer simulations to coevolve robot bodies and controllers, which were then 3-D printed and physically tested (55). A recent proof-of-concept study (56) demonstrated the workflow and supporting infrastructure to allow an initial population of two physical robots to go through a life cycle and produce an offspring robot. In related work (57, 58), modified industrial robot arms functioned as mother robots that automatically constructed, evaluated, and evolved simple robotic vehicles. In these early demonstrations, it is natural to choose locomotion as the desired ability to improve, since locomotion is easier to develop than more complex tasks like manipulation or assembly. In addition, the mother robots are substantially more complex than the robot offspring being created and evolved. But as the technology progresses, the capabilities of the offspring will naturally increase. Though it is not an easy goal, self-reproducing robots could plausibly leverage open-ended evolution to create new and surprising methods of manufacturing.

4.4. Nanotechnology

In the 1990s, Drexler (59) popularized a vision of atomically precise manufacturing. Self-replicating nanoscale robots called molecular assemblers play a prominent role in this vision, creating atomically precise products and amplifying manufacturing power through self-replication. Richard Feynman is often credited with originating the vision of nanotechnology in his 1959 lecture "There's Plenty of Room at the Bottom" (51). Interestingly, while some nanotechnology researchers acknowledge that they drew inspiration from Feynman's lecture (60, 61), many apparently were unaware or uninfluenced by his ideas (50, 62), including Drexler himself, who conceived his own vision of nanotechnology prior to learning of Feynman's lecture (63).

Drexler's vision of nanotechnology via self-replicating nanobots drew harsh criticism from the scientific community (64–68), for reasons including the perceived infeasibility of mechanically controlled chemical synthesis and the general notion of nanoscale self-replicating robots. A fascinating account of the tension between optimistic nanotechnology "futurists" and skeptical "scientists" is given in the aptly named paper "Rage Against Self-Replicating Machines: Framing Science and Fiction in the US Nanotechnology Field" (69). The established scientific community's hostility toward Drexler's ideas is evident in the tone of numerous articles (e.g., 62, 70). In recent years, some of this hostility has begun to thaw (71, 72). Drexler has scaled back some of his visions of nanotechnology, and self-replicating nanorobots no longer play as prominent of a role (73). Meanwhile, as the scientist/futurist debate played out, other researchers made steady progress in the lab (74). The 2016 Nobel Prize in Chemistry was awarded "for the design and synthesis of molecular machines" (75, p. 158), and researchers have recently demonstrated chemical reactions mechanically catalyzed by simple nanoscale devices resembling robot arms (76). Perhaps Drexler's radical predictions will turn out to be accurate after all.

5. UNIQUE CHALLENGES OF SELF-REPRODUCING ROBOTS

Creating a complete self-reproducing robot system will require solving several special problems. While none of these problems are intractable, many of them have simply not received much attention because they are unique to self-reproducing systems and often do not have broader applications in robotics or engineering.

5.1. Materials, Tools, and Processes

The materials, tools, and processes for producing components from raw materials must be carefully chosen so that the self-reproducing system can fabricate its own constituent components. For example, if cutting tools are to be used, there must be tools and processes that form and sharpen the cutting tools, although ultimately the cutting tools will be hard enough to cut and form the tools that made them. [This was in fact a difficult problem to solve in the early history of human-in-the-loop manufacturing (77).] These kinds of self-referential loops are ubiquitous in self-reproducing machine design (78), and most of the unique problems to be addressed resemble them in some form or another.

Unfortunately, solid free-form fabrication does not inherently offer a work-around for this problem. While there has been dramatic progress in the ability of both industrial and consumer 3-D printers to create multifunctional, multimaterial objects, this ability typically comes at the cost of even greater complexity in the details of the deposition mechanisms. Even a sophisticated 3-D printer, for example, is not capable of printing its own nozzles, extruders, or motors.

5.2. Assembly Error Tolerance

A robot manipulator will have some error in the position of its end effector due to imperfections in manufacturing, random disturbances from the environment, and so on. A complex and precise modern assembly robot can have a very low positioning error, but typically these robots also demand high-quality components that are challenging to build and assemble. In certain applications, simple robots made of basic components that are more tolerant to assembly errors may be more advantageous in a self-reproducing context. Moses et al. (29) discussed this trade-off in detail.

Demonstrations that involve simple robots assembled from simple components sometimes rely on magnets (32, 79) or electromagnets (80, 81) to perform connections. This allows for a greater tolerance to misalignment, as well as a self-corrective pull-in effect from the magnetic force. Purely mechanical locking mechanisms using tapered surfaces (82) or actuated hooks (83) have also been used.

Industrial robots (see also Section 7.4) that assemble similar devices rely on computer vision and force sensing, and even then some tasks are still left for humans (84).

5.3. Controllers

In some cases (e.g., space-based manufacturing), it may not be necessary for the self-reproducing system to build its own controllers. Microprocessors could be supplied from Earth as vitamins (see **Figure 5**), and difficult tasks could be guided or even performed by humans over telemetry. Chirikjian et al. (38) have described prototype robots demonstrating remotely guided self-replication, and Jones & Straub (85) presented an autonomous command and control approach for a practical self-replicating system.

For other applications, especially those hoping to leverage open-ended evolution, it may be desirable or essential for the system to build as much of its own controller as possible. A number of studies have looked at this idea. Stevens (86) designed and simulated an entire self-replicating universal constructor at a low level of detail, including a controller made of individual logic gates. In a later project, Stevens (87) investigated the feasibility of using scratch-built relays and 3-D-printed motors to control a simple plotting machine that would read instructions stored on punched tape. Several track-guided self-replicating robots controlled by simple distributed relay circuits have been demonstrated (88, 89), as have other electromechanical replicating devices (90). Malone & Lipson (91) described proof-of-principle free-form fabricated relays, and there has been resurgent interest in purely mechanical computers and controllers that can be 3-D printed (92). Finally, in some cases the replication of physical devices can take place without any controller at all (24, 93).

5.4. Robot Workspace

A self-reproducing robot (or a system of robots that collectively self-reproduce) must build something as large as itself, and during construction the parent robots must be able to access all of the workspace necessary to place the required components. This can be accomplished in several ways, including the use of tracks to guide mobile manipulators (32, 79, 88), the use of conveyors to move the workpieces (94, 95), changes in the configuration of the robot offspring during assembly to facilitate access by the parent robot (29, 80, 96), and the use of a growth period after the creation of an offspring smaller than the parent (97).

5.5. Calibration and Generational Error Correction

In many applications, self-reproducing robots would not need to self-calibrate or correct their own errors. In a space-based manufacturing application, for example, measurement standards could be supplied as vitamins, and the calibration processes could be performed by humans over telemetry. In other cases, such as a pure-bootstrapping or evolutionary application, robots that reproduce themselves for multiple generations must have the ability to correct generational errors. In human-in-the-loop industrial processes, there are multitudes of techniques (98) to separate the errors in measuring instruments from errors in produced parts, allowing for self-calibration of the instruments and absolute testing of the parts in the absence of an externally defined standard. Typically there is no need to automate this process: From semiconductor fabs (99) to automobile plants (100) to the robot factories of FANUC (84), before machines can make other machines they are first set up, calibrated, and fine-tuned by humans. Although the detailed implementation of an automatic error-correction process would require original research, it is plausible that such a method could be developed.

6. THEORETICAL AND COMPUTATIONAL WORK

As stated in Section 2, von Neumann's ultimate goal was the development of a systematic theory; the design and construction of practical machines was secondary to this main goal. The large body of modern work extending from von Neumann's foundational ideas tends to similarly emphasize theoretical development over practical robot design, and as such is somewhat outside the scope of this review. The interested reader is referred to reviews on, e.g., artificial life (17). The subset of theoretical studies discussed in this section are chosen for their relevance to robotics applications.

6.1. Extensions of von Neumann's Early Work

In an effort to approach the problem of robustness to manufacturing errors, in 2003 Sayama (101) extended von Neumann's logical model to include a workplace that would assist construction. In 2007, Lee & Chirikjian (32) extended the logical model to include aspects of energy supply, waste management, and the constructor environment, applying the model to develop complexity measures for self-reproducing systems.

Menezes & Kabamba (102, 103) presented algorithms for determining optimal seeds, i.e., optimal sets of elements necessary for self-reproduction. In 2011, Kabamba et al. (33) developed the concept of a generation system to determine the minimum information required to specify a seed that could reproduce without degeneration. Gitik (104) considered an alternative definition of this generation system, provided a solution for finding optimal seeds, and showed a connection between self-replication and fixed-point theory. In related (but earlier) work, in 2008 Sayama (105) proposed the interesting conjecture that nondegenerative self-reproduction in a universal constructor is equivalent to a universal computer attempting to solve the halting problem. The hint of fascinating interconnections between these different topics suggests that this area is fertile ground for future research.

Building on the concept of von Neumann's cellular model, Stevens (86, 106) developed an extensive kinematic simulation environment that culminated in the simulation of a massive self-replicating universal constructor. The custom-made environment allowed the design of a constructor that is much closer to reality than is typically possible in a formal cellular automaton model (e.g., 107).

6.2. Artificial Chemistries

Artificial chemistries simulate the dynamics of virtual molecules that move and interact via rules that, while inspired by real chemistry, are more abstract and do not capture many of the microscopic details of real chemistry. They can provide insights into complex phenomena that are difficult to study in less abstract models (108). Artificial chemistries have been used to implement systems reminiscent of DNA replication (109–111) as well as much more complicated systems resembling membrane-bound cells (112, 113). The membrane plays a critical role in the reproduction process, and a similar membrane structure could be especially useful in robotic systems made up of many interacting subunits. However, with the exception of studies by Kriesel et al. (114) and Yu et al. (115), there seem to be relatively few investigations of this idea.

6.3. Complexity and Performance Metrics

As stated in Section 1, to our knowledge there are at present no examples of a robotic system that completely self-reproduces. There are numerous instances of devices that partially self-reproduce, but due to their great variety, it is often unclear what this partial self-reproduction means. Quantitative measures of a system's self-reproducibility are of more than academic interest—they can help us to evaluate and design better and better systems. One notable example is the description of kinematic replicator design space developed by Freitas & Merkle (8) in 2004, comprising "137 practical multivalued replicator design properties which may be grouped into 12 primary design dimensions in four principal categories" (p. 152).

Most current physical demonstrations of partially self-replicating robots are made of modular building blocks that in one form or another resemble von Neumann's original idea of "unambiguously defined elementary parts." Lee & Chirikjian (32) proposed a metric called the degree of self-replication to quantify this property of robots composed of modules. The number of active elements is counted for each module, along with the number of interconnections between modules when assembled into a complete system, where an active element is defined as a moving part or fundamental electronic component. The degree of self-replication then measures the ratio of the overall system complexity to the complexity of the input parts. For example, a system made of few very complex modules would have a very low degree of self-replication, and one composed of many very basic parts would have a high degree.

Another metric proposed by Chirikjian and colleagues (34, 116) builds on Sanderson's (117) concept of parts entropy. This metric measures the contribution of the robot by comparing the parts entropy of the system before and after assembly. A related information-based metric proposed by Adams & Lipson (35) treats self-replicability as a continuous property of a system. Their metric is extrinsic and independent of the details of how the system works, whereas the metric proposed by Chirikjian and colleagues (34, 116) is intrinsic, depending on knowledge of how the system is constructed.

7. PHYSICAL DEMONSTRATIONS

A wide variety of physical prototypes related to robot self-replication have been demonstrated. **Figure 6** shows graph network representations for four types of systems: industrial robot assembly lines, track-following robots, reconfigurable modular robots, and RepRaps. Some of the machines presented here are designed explicitly with self-replication in mind (25, 29, 30, 34, 79, 80, 93, 118), some are not (28, 119), and some are equipped to perform self-replication incidentally as a subset of broader capabilities (96, 120).

Regardless of whether the systems are capable of (or even designed for) self-replication, the common thread in these diverse examples is the idea of robots that, in von Neumann's words, have "outputs something like themselves" and are composed of "unambiguously defined elementary parts." In a modular robot system, the outputs are assemblies of modules. In 3-D-printer examples, the outputs are printed components that could be used in other 3-D printers, and the elementary parts are defined by the available materials and geometric properties of the machine (e.g., layer height and voxel resolution).

The modular robotic systems considered here range from simple passive components with no onboard processing (22, 93) to complex mobile systems that are robots in their own right (119, 121). It is worth noting that the apparently organic division of research projects into two separate groups—modular robots and 3-D printers—closely parallels the architecture proposed by Hall (31), which uses two types of constructing machines, classified as either fabricators or assemblers. There are, of course, a few interesting edge cases that blur the distinction between fabrication and assembly; examples include a mobile robot that creates structural modules using foam adhesive (122), a manipulator that can glue modules onto itself (123), and modules that can solder themselves together (124).

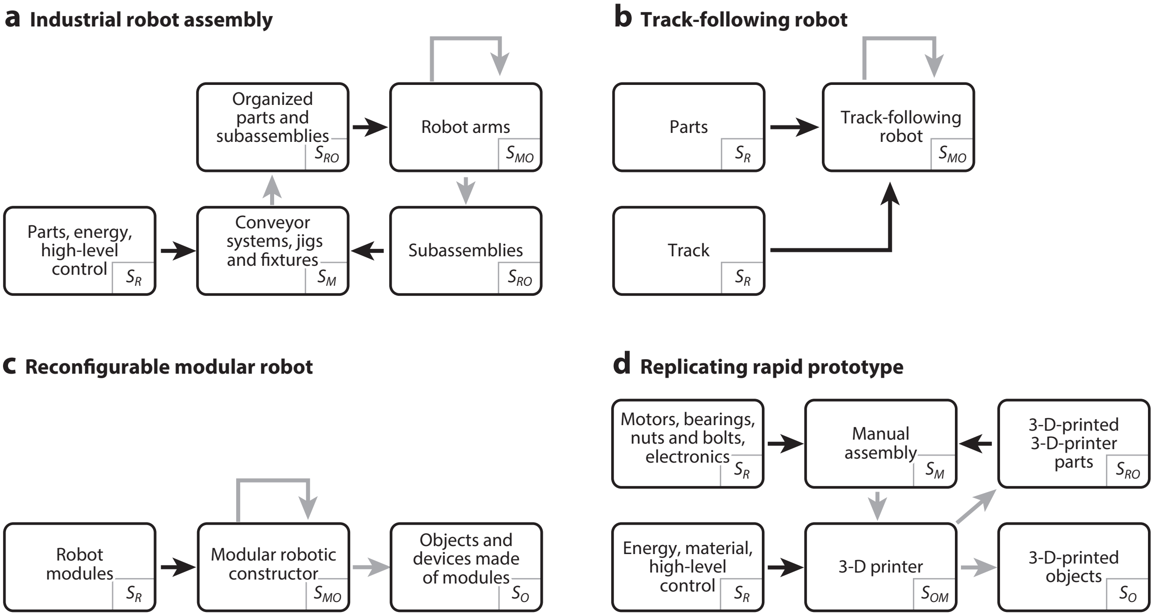


Figure 6

Graph network representations for different self-replicating or partially self-replicating systems: (*a*) industrial robot assembly lines (84), (*b*) track-following robots (32, 79, 88), (*c*) reconfigurable modular robots (80, 96), and (*d*) replicating rapid prototypers (3-D-printer-based partially self-replicating systems) (46, 47).

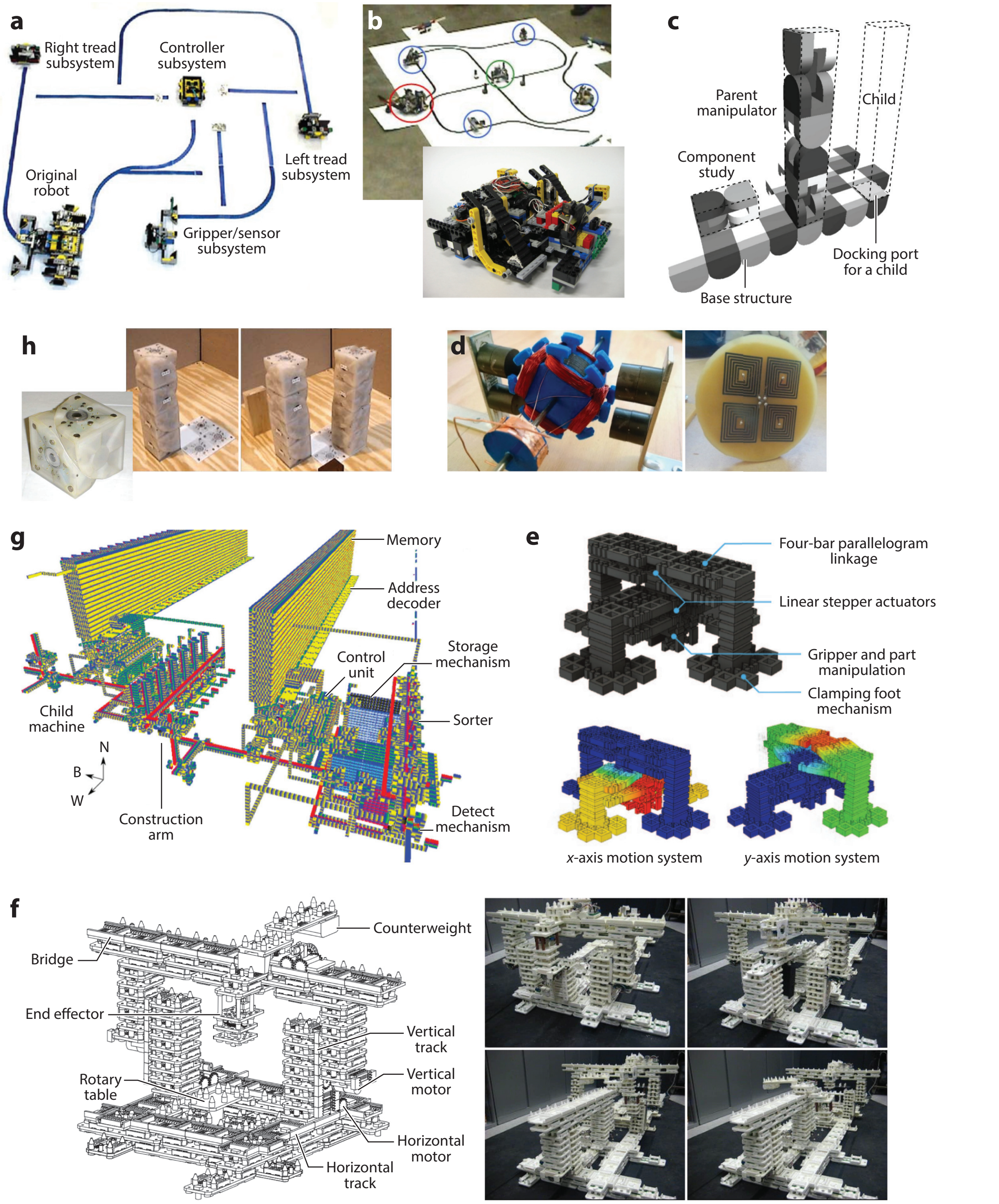
7.1. Robots Built from Modular Components

A large number of modular robotic platforms have been prototyped. The fact that researchers as far back as 2006 were giving their robots names like YaMoR (Yet Another Modular Robot) attests to this. We can only scratch the surface of this literature; for additional reviews, see References 10, 13, and 14. **Figure 7** shows a collection of modular robotic devices capable of some level of self-replication.

The Chirikjian group has developed several robot systems designed for self-replication, self-repair, and universal construction. These systems include a variety of track-guided constructors that assemble duplicates from simple modules (32, 34, 79), a set of mobile modules that perform hierarchical self-replication (25), mobile modules that perform self-reconfiguration and self-repair (120, 125), and a gantry-style constructing robot made from a set of simple electromechanical parts (29).

The initial gantry robot and associated track system (shown in **Figure 7*f***) contain approximately 100 parts. The robot is designed to extend the track system and then assemble a duplicate robot when supplied with an orderly stack of parts. The critical steps for self-replication were demonstrated in a series of tests.

The Molecubes system (**Figure 7*b***), developed by the Lipson group, uses a single type of cubical module containing a motor, microprocessor, and electromagnetic connectors. Constructors made of these modules have demonstrated self-replication, self-repair, and self-reconfiguration (80, 81). The M-TRAN system (**Figure 7*c***), developed by the Murata group, is a highly capable and well-studied modular robot system. Like the Molecubes, it is based on a single type of module and has demonstrated self-replication, self-repair, and self-reconfiguration (96, 126).



(*Caption appears on following page*)

Figure 7 (*Figure appears on preceding page*)

Examples of different self-replicating systems. Clockwise from top left: (*a*) a track-guided replicating robot with microprocessor control, (*b*) a track-guided self-replicating robot with reduced complexity control, (*c*) M-TRAN (Modular Transformer), (*d*) prototype 3-D-printed motor components, (*e*) a digital material universal constructor, (*f*) a universal constructor made of simple modules, (*g*) a kinematic simulation of a universal constructor, and (*h*) Molecubes. Panels *a–c* and *e–h* adapted with permission from References 79, 34, 96, 30, 29, 86, and 81, respectively. Panel *d* adapted from Reference 133 with permission from MIT Press under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0) license; copyright 2017 Massachusetts Institute of Technology.

7.2. Digital Material Printers

A digital material printer is a device partway between an assembly robot and a 3-D printer. Small, simple, uniform building blocks are used as the raw material (as opposed to the bulk filaments or resins typically used in 3-D printers). The printing device relies on the regularity of the input blocks to produce strong, complex, and highly precise objects (127). A wonderful (if not entirely practical) demonstration of the concept is a 3-D-printer-like device made with LEGO building blocks that can create arbitrary combinations of simple blocks (128, 129). Langford et al. (130) developed a printer device and associated set of building blocks to enable electronic digital materials. In principle, a constructing robot made of these building blocks can assemble other blocks (30).

7.3. 3-D Printers and Free-Form Fabrication

The RepRap 3-D printer (46) is widely described as partially self-replicating because it can print some of its own parts. A graph network representation of a RepRap is shown in **Figure 6*d***. Projects like RepRap (46) and Fab@Home (45) were instrumental in starting the low-cost 3-D printer revolution. While self-replication was a focus of the early RepRap project, most low-cost 3-D printers on the market today are made by traditional (non-3-D-printed) manufacturing methods. Two difficult problems must be addressed to build a fully self-replicating 3-D printer: the elimination of the human in the loop required for assembly, and the creation of additional network loops to allow the production of things like motors, extruders, and linear bearings from raw materials. In an attempt to address the first problem, several studies have looked at combining 3-D printers with other technologies to allow self-replication (85, 131–133), but to our knowledge there have been no demonstrations of, say, a 3-D-printed modular robot capable of postprocessing and assembling 3-D-printed parts without human intervention.

In all cases of which we are aware, even remarkable demonstrations of free-form fabrication [such as the creation of actuators (134) or even functional soft or self-folding robotic bodies (19, 135)] rely on at least some human intervention and involve a significant degradation in performance when compared with the abilities of the fabricating machine. As with assembly robots, more complex is not necessarily better in a self-reproduction context (see Section 5.2). In self-reproducing applications, simple fabricators made of basic error-tolerant components may be more advantageous than complex machines that rely on sophisticated manufacturing processes. Numerous studies have advanced the state of the art in printing objects that would be of practical use in a self-replicating 3-D printer, including prototypes for 3-D printed solenoids and electromagnetic motors (78, 131, 134), methods for printing circuits from highly conductive plastic (136), 3-D electrical traces in plastic using metals with a low melting temperature (137), electroforming plastic extruder nozzles using plastic and metals with a low melting temperature (138), and printed rotary bearings, linear bearings, and leadscrews (118, 139).

7.4. Industrial Robots

Several industrial robot companies use their own robots to build more robots. For example, the German manufacturer KUKA markets a robotic workcell that uses a robot manipulator and two machining centers to drill, mill, and deburr cast robot components (95). The Japanese company FANUC, one of the largest producers of industrial robots in the world, reportedly makes extensive use of robot automation in the production of its industrial robot products. By many accounts, FANUC is highly secretive, so publicly available details of its robot assembly lines are sparse (84, 140, 141). The company website states that robots are used to assemble motors, servo amplifiers, parts of machining centers, and additional robots (142). While much of this process appears to be highly automated, company officials state that certain tasks (like wiring) are performed by humans (84). In general, a robotic assembly line must be meticulously set up and fine-tuned by humans prior to operation (94). In contrast to RepRaps and reconfigurable modular robots, the assembly line cannot be quickly reconfigured to produce different outputs without significant human intervention.

7.5. Chemical and Biochemical Systems

Supposing, hypothetically, that a nanoscale, self-reproducing robot could be made of chemical building blocks, it would likely qualify as a life form. Several researchers have worked on defining the transition between living and nonliving matter, including Rasmussen et al. (143, 144), Solé et al. (145), and Sugiyama & Toyota (146). There is some resemblance between the questions addressed by these researchers for systems at the molecular level and the efforts to define performance metrics for robots discussed in Section 6.3.

The boundaries between robotics, materials, and chemistry are becoming ever more blurred. For example, in 2008, Randhawa et al. (18) demonstrated a chemically actuated microgripper, and in 2016, Wehner et al. (19) demonstrated a prototype 3-D-printed soft robot, including rudimentary control and actuation, all without any traditional electromechanical devices.

The field of DNA origami has seen tremendous progress in recent years. Custom DNA sequences can form self-replicating tiles (147) and other objects (148) that in many circumstances can behave similarly to macroscopic robotic building blocks (149). In 2018, Kopperger et al. (150) demonstrated an electrically controlled, self-assembled "robot arm" (albeit one with a single degree of freedom) made of DNA building blocks. These studies demonstrate that the building blocks for nontraditional, chemically or biochemically based robots are available.

8. CONCLUSIONS AND FUTURE DIRECTIONS

The concept of artificial self-replicating robotic systems has attracted attention in the scientific community for many decades. Self-replicating robots have also featured significantly in works of science fiction, where they seem to inevitably result in the demise of humanity. In the real world, nonbiological self-replication is very difficult without human supervision and is fraught with many fragile steps. With the recently renewed interest of many nations and private companies in space exploration, the concept of self-replicating robotic systems has again surfaced as a potentially beneficial technology. Perhaps it is the only feasible paradigm for scaling up the use of in situ resources to make structures for human habitats in space and to harness the tremendous clean energy resources that are currently unavailable for humanity's benefit.

Many challenging research problems remain open in the design of robots, materials processing, and manufacturing technologies. With the historical perspective provided and the technological bottlenecks identified here, we hope that this review will facilitate the advancement of future work in this area.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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