Robot Makers: The Future of Digital Rapid Design and Fabrication of Robots

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Robots are complex systems, and their design requires detailed knowledge of diverse fields including mechanics, electronics, software, and control theory. Thus, our ability to rapidly create robotic systems requires a synergy between these diverse disciplines. In the near future, new paradigms and tools will be needed for on-demand design generation; new fabrication methods will be needed to realize custom electromechanical devices; and new algorithms and programming languages will be necessary to define, evaluate, and optimize behavioral specifications and designs. In this work we assess the main challenges, problems, vision, and future steps on the topic of co-design and rapid fabrication of robotic systems.

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1 Introduction

Recent advances in design, fabrication, and programming technologies promise to enable the rapid digital manufacturing of functional robotic systems. However, many challenges remain to be addressed to realize the dream of fully functional print-on-demand robots. The design of robotic systems requires expertise in diverse areas including mechanics, electronics, software, and control theory. Contributions from all of these fields will be required in order to automate or at least greatly simplify direct robot fabrication.

In this paper we explore current and future directions of robotic development and more specifically we focus on the following topics of discussion: fundamental approaches to robot manufacturing methodology ranging from a traditional assembly model to an emerging material model; the near-ubiquitous use of rapid prototyping and its effects on concepts of manufacturability and verification; the changing definition of robotics with the emergence of new sub-fields as well as through the loss of mature sub-fields spinningoff into separate disciplines; and the evolving nature of the maker culture in the context of robotics.

Salient research directions that promise to inform the future of robotics are: (i) advanced design and manufacturing approaches that aim to circumvent some of the challenges of traditional technologies; (ii) the application of software development techniques on electromechanical synthesis; (iii) integrating and co-generating all aspects of a robot to include mechanical, (iv) electrical, and software sub-systems; (v) incorporating compliance in robotic development; (vi) and robots improving human lives through unprecedented levels of interaction, especially in medical settings.

The remainder of this article is organized to provide an overview of contributions and research activities as they relate to robot making in three fundamental directions: Design, Fabrication, and Software Development. We then conclude with a discussion of open research challenges and anticipated near-term solutions.

2 Design of Robotic Systems

Designing a robotic system requires translating the definition of the desired electromechanical device between various types of specifications. The design process often starts with a functional specification, describing the system's intended behavior. The ultimate goal of design is to end up with a set of fabrication specifications that can get sent through a manufacturing process to make the robot. This flow can be split with an intermediate structural specification that realizes functionality in terms of mechanisms and assemblies. Research into design systems for robots aims to assist users in the creation of fabricable drawings directly from structural or functional specifications.

Design for manufacturability (DFM) considerations impose constraints on functional and structural specifications based on limits of fabrication technology. By expanding the manufacturing capabilities, these constraints can be relaxed, or ideally eliminated. For example, current 3D printing technology allows for nearly any rigid bodies to be fabricated, thus allowing for direct realization of arbitrary functionally specified solid structures. It is towards this goal that robotic design research is aimed: the ability to make arbitrary functionally specified mechanisms.

2.1 Compliant Materials and Soft Robots

With an increasing emphasis on soft robotics in the community, DFM for compliant materials and manufacturing processes is an active area of research. Compliance in structural elements adds another dimension to the design space which needs to be incorporated into the design flow. By examining hybrid structures and composite metamaterials, Wehner et al. demonstrated how to fabricate structures with a range of material properties [1], as shown in Fig. 1. A related fabrication process presented by Menguc et al. (Fig. 2) [2,3], was used to manufacture soft sensors designed using a functional specification.

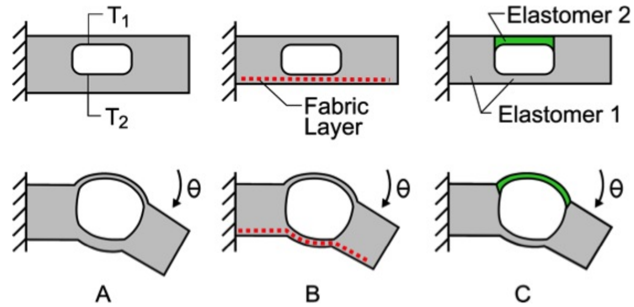


Fig. 1. Multimaterial designs allow structures to be manufactured with a wide range of stiffnesses. Different methods to design and fabricate bending actuators: (A) Asymmetrical geometry, (B) Inextensible (fabric) layer, and (C) Elastomers of different moduli. Courtesy of Michael Wehner [1].

2.2 Origami-inspired Folding

In contrast to the solid objects generated by 3D printing, mechanical structures can instead be fabricated by folding their surfaces from a patterned 2D sheet in a manner similar to the Japanese art of origami. This process has been used to create robotic bodies out of sheets of paper, plastic film, and multi-layer laminates [4–6]. This process has advantages over other rapid manufacturing techniques: it is faster due to a subtractive rather than additive process, and it allows for inbuilt compliance due to the flexible stock material. However, generating a correct 2D unfolding to realize an arbitrary 3D structure poses a significant design challenge.

Theoretical geometric analysis of 2D unfoldings has resulted in a process by which provably correct complex structures can be designed by the composition of simpler assumed correct structures, and a construction is shown by Sung et al. in [7]. This work was follewd up with an analysis of a multitude of folded joints to effect a wide range of degrees of freedom in [8], and together they form a theoretical basis for the algorithmic design of folded mechanical structures. This has been adapted into a design environment for the creation of custom folded robots in [9]; further discussion of such software design environments is provided in Sec. 4.

2.3 Integrated Electromechanical System Design

In addition to structural elements, robotic design must also take into consideration electrical and software subsystems. The electronic control system hardware shown in Fig. **??** was designed to fly miniature quadrotors presented in [10] using a modular electronic design environment. More generally, the work presented in [11] allows the design of C++ and Python skeleton codes using an architectural description language for the control of robotic systems and similarly [9] allows modular cogeneration of electronic and software blocks to control a more general collection of robots from a description of its mechanical structure. All of these systems generate fabricable designs including circuit schematics, layouts, wiring diagrams, and firmware and software packages, from higher level functional specifications. Again, a more detailed discussion about software tools follows in Sec. 4.

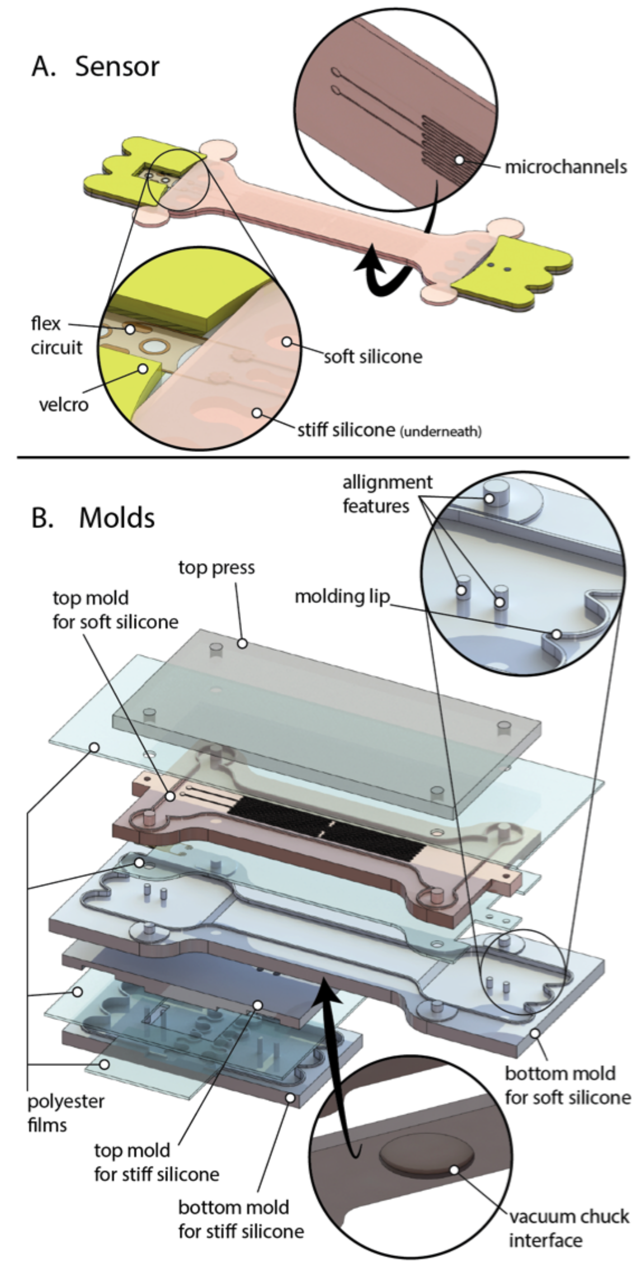


Fig. 2. Advanced manufacturing processes can realize the functional specification of a soft sensor, which calls for a range of material properties [2, 3]. Courtesy of Yigit Menguc.

These advances in robotic design systems and techniques provide a number of broad benefits in expanding the reach of robotics. With domain specific engineering knowledge handled by a design environment, casual users can design robots at a higher level of functional specification. With less training needed to create custom on-demand robots, such research can democratize robot making. Though there are tradeoffs between on-demand robotic design as compared to expert design of more general multi-purpose robots (see Sec. 5 for further discussion), several use cases can be identified for bespoke robots. Applications in art, education, and the developing world can benefit from a custom robot design system.

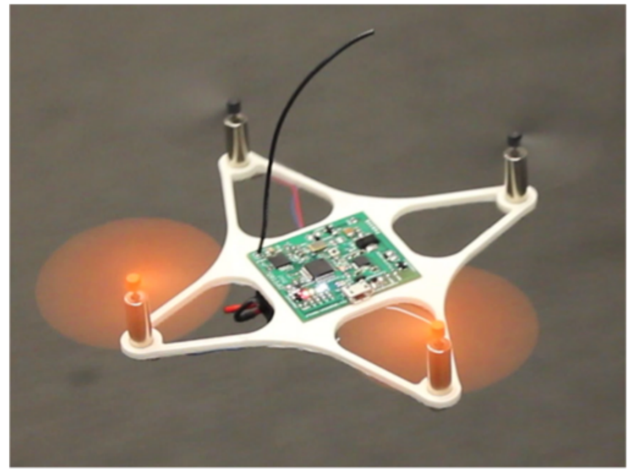


Fig. 3. This flight control circuit and frame was designed using a modular description of its desired functionality. Courtesy of Yash Mulgaonkar [10].

3 Fabrication Techniques

3.1 Additive Manufacturing

New approaches to additive manufacturing are key enablers of the rapid fabrication of robots. Advances in 3D printing technology [12] have allowed the direct 3D printing of everything from audio speakers [13], to batteries [14], to soft strain sensors [15]. Current research has just begun to explore the range of printable materials, processes, and designs that may be possible.

While researchers use 3D printing primarily for the fabrication of structural components, there is an increase use of 3D printing technology in the fabrication and testing of robotic systems. For example, Melo et al. combined 3D printing of their mechanical system and open source electronics hardware and software solutions to rapidly develop modular variable impedance actuators [16] (Fig. 7). Menguc et al. used 3D printed molds to rapidly fabricate soft sensors with discretized stiffness gradients [2, 3] (Fig. 2). Bunting and Sprinkle made extensive use of 3D printing to manufacture the structure of a biologically inspired hexapod robot [17]. They found that 3D printing allowed for the rapid iteration of complex bioinspired designs at the physical level (as well as in simulation), which would have been prohibitively expensive otherwise. Mulgaonkar and Kumar even made use of 3D printed parts for their ultra lightweight quadrotor to connect the propeller motors to the main printed circuit board [10] (Fig. **??**). Correll and Voyles propose extending beyond the fabrication of passive structures with 3D printers using carbon-infused acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) filaments to embed conductive parts [18].

On the testing and characterization side of robotic system design, Drew et al. made a very interesting use of 3D printing technology for their micro air vehicle propelled by atmospheric ion thrusters. They used 3D printing not to fabricate their robotic system (they required lighter weight materials like balsa wood), but to fabricate a complimentary force measurement system [19] (Fig. 4). Since the forces they were trying to measure were very small (down to 0.1 mg), and the high electric fields required for electrohydrodynamic thrusters affect the accuracy of sensitive electronic scales, they chose to 3D print a test apparatus with compliant features that move measurably in response to small forces. 3D printing allowed for rapid fabrication and iterative sensitivity adjustment of the test apparatus.

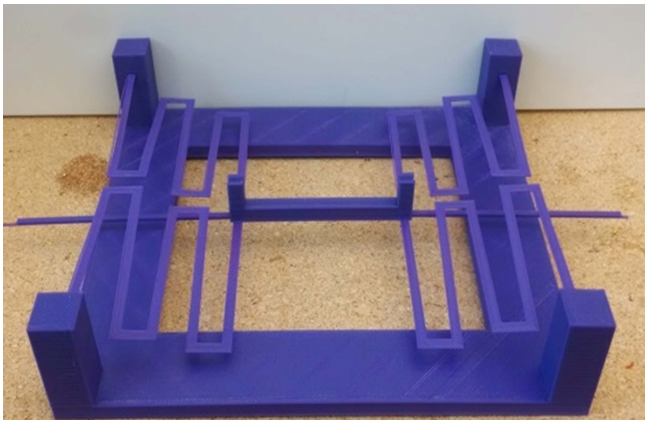


Fig. 4. 3D printed test apparatus for measuring small forces from electrohydrodynamic thrusters. Courtesy of Joseph Greenspun [19].

Another additive manufacturing technique of particular interest to robotics is Shape Deposition Manufacturing (SDM) [20]. SDM systematically combines material deposition with material removal to enable the rapid fabrication of complex, multi-material parts. In robotics, SDM has been used to fabricate hexapedal robots [21], compliant graspers [22], and robotic parts with embedded electronics [23] or sensors [24]. Correll and Voyles also proposed a compelling application of SDM as a way to integrate electronics into polymers or metals to achieve robotic materials [18].

Recent work has employed additive-subtractive processes similar to SDM called Printed Circuit Microelectomechanical Systems (PC-MEMS), which are used to manufacture electromechanical laminates that are subsequently folded into robotic systems. This approach has been employed to fabricate insect scale walking [25, 26] and flying robots [27]. While the resulting devices are complex and capable, fabrication still requires a great deal of skill and time. Subsequent work has focused on developing pop-up book inspired approaches to the assembly of folded devices [28].

Building on this idea, another approach has aimed to use less complex and automatable fabrication processes in order to realize "print-and-fold" robotic systems or "printable robots" [29]. To address the key challenge of automating folding, related work has developed self-folding laminates which use shape memory polymer layers to achieve self-folding structures [30] (Fig. 5), devices [31], and robots [32]. Aukes et al. presented an analytical framework and associated free software, popupCAD, to guide the design and fabrication of these types of laminate manufactured systems [33] (Fig. 6) (www.popupcad.org). This tool can be used for the design of devices for print-and-fold manufacturing as well as related laminate manufacturing approaches such as SDM.

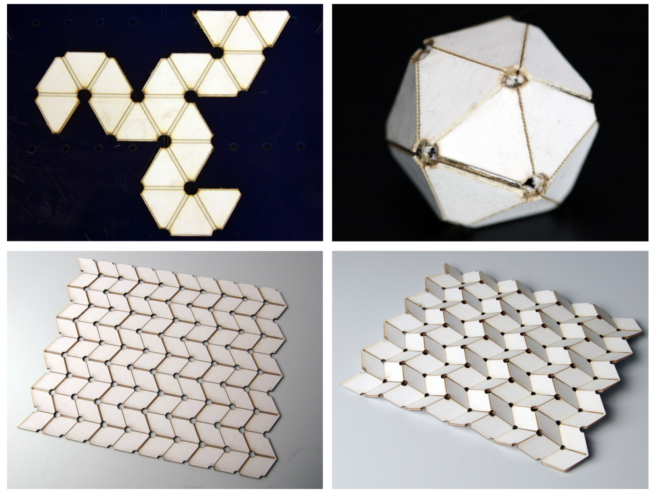


Fig. 5. Printed self-folding shape memory laminates before (left) and after (right) activation by uniform heating [30].

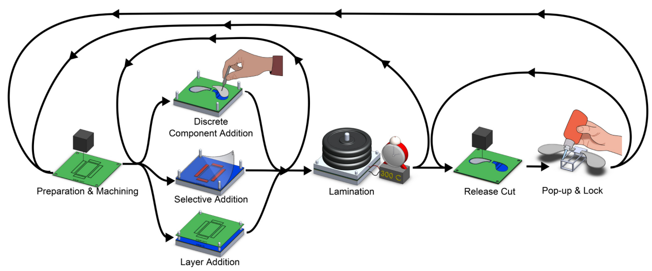


Fig. 6. Overview of general PC-MEMS fabrication process for robot fabrication from laminates. Courtesy of Daniel Aukes [33].

3.2 Soft Robotics

Soft robotics offers an unconventional, emerging approach to incorporating compliance into future robotic systems. As such, there are many open research questions on appropriate methodologies to create not only passive bodies, but also active and functional elements interacting safely and seamlessly with the environment. The resulting robots are often bio-inspired, enabling synthetic counterparts of the impressive mobility and manipulation capabilities observed in nature.

Extending traditional capabilities by 3D printed plastic assemblies integrated with discrete springs, Natural Motion Initiative demonstrated variable stiffness actuators (VSAs) as a modular tool to rapidly prototype several robotic capabilities [16]. Fig. 7 displays the VSA - Cubebot, a modular and compact variable stiffness actuator, which can independently and simultaneously adjust both the equilibrium position and the output stiffness of a rotary shaft using two signals. With electrical and mechanical modularity, these actuators can be connected in different ways to realize robot prototypes for a broad range of applications.

Fig. 7. Variable Stiffness Actuators - CubeBots. Courtesy of Antonio Bicchi [16].

For high levels of compliance, elastomeric materials offer a promising approach to the manufacture of truly soft robotic systems. Commonly processed through molding in liquid form, extremely detailed robot bodies, actuators, and sensors can be achieved. A significant challenge in this research direction is a lack of formal methods for the development of rubber-like systems. A potential solution is proposed in the form of the Soft Robotics Toolkit, which provides a collection of resources, including CAD models of tested designs, fabrication recipes, and preliminary analysis tools [34]. A conceptual use-case of the Toolkit is depicted in Fig. 8.

Robots fabricated from elastomer are not necessarily limited to a single material. Combinations of multiple materials may be advantageous to yield desired deformation responses as depicted in Fig. **??**, especially for actuation [1]. Similarly, compositions of traditional mechanical components with elastic materials have been shown to reduce unnecessary deformations and hence utilize the actuation energy more efficiently for predictable motion outputs [35] (Fig. 9).

4 Software Environments

Software plays an important role both in the design and in the implementation of robotic systems. From a design perspective, several tools are currently available to aid a user through the process of creation, drawing, and automatic generation of mechanical, electronic, and software specifications. Software should support design and code reusability, simplify the design process, automate the design and generation process as much as possible, and eventually support verification and validation of the developed final product.

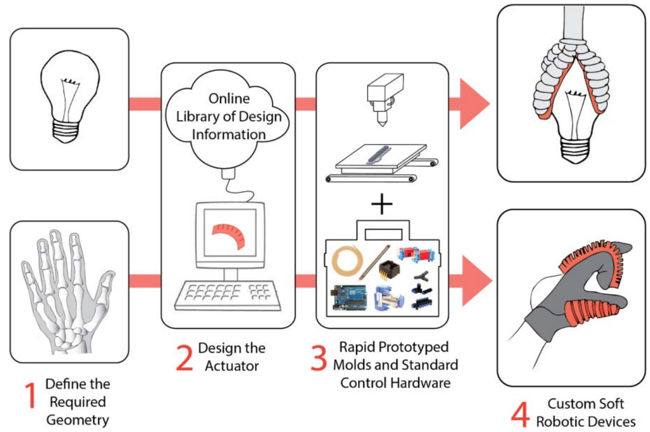


Fig. 8. Conceptual soft robot development process using common virtual and physical platforms to support a range of applications. Courtesy of Conor Walsh [34].

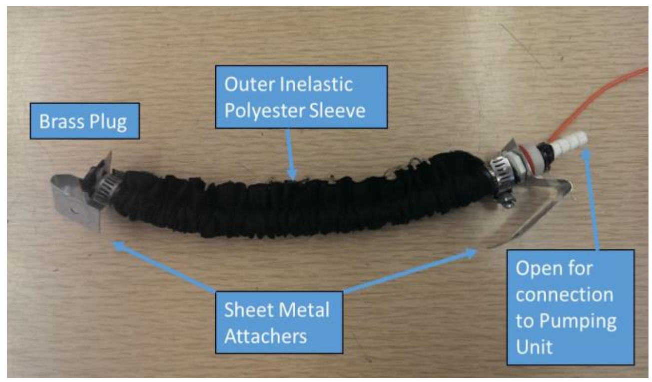


Fig. 9. Hydraulic Artificial Muscle (HAM) prototype consists of an elastic tube covered with an inelastic material that limits the expansion of the actuator in the radial direction, but not in the longitudinal direction [35].

A robotic system is a synergy between many fields of study including mechanics, physics, chemistry, electronics, software, and control theory. Typically during the development process, these diverse aspects of system development are handled by different groups which require different expertise. Historically, control engineers, embedded software developers, mechanical engineers, system integrators, etc., worked separately. However, rapid prototyping of robotic systems demands closer collaboration between these groups and requires processes that support such closer collaboration. At the same time, tighter interaction between different aspects of the system requires a focus on the interfaces between them. Control designers should be more aware of capabilities of the embedded platform, while designers of embedded networking should take chosen control strategies into account when planning communications within the system. This makes integration of the system more challenging, since a change in one aspect of the system renders other aspects inconsistent. Furthermore, it is necessary to incorporate architectural modeling of the system as part of the design process, to ensure that each system component/functionality remain consistent with any architectural and system changes.

The importance of the architectural system modeling has led to the development of the Architecture Analysis and Design Language (AADL) [36] for the modeling of hardware and software architectures in embedded systems. AADL includes software, hardware, and system component abstractions to: (i) specify and analyze real-time embedded systems, complex systems of systems, and specialized performance capability systems and (ii) map software onto computational hardware elements. Within the AADL, a component is characterized by an identity name, possible interfaces with other components, properties, and subcomponents and their interactions. This tool, frequently used in industry, can model and analyze systems already in use and design and integrate new systems. The AADL can be used in the analysis of partially defined architectural patterns as well as in full-scale analysis of a complete system model extracted from the source code.

4.1 Generation of software components.

Following the AADL framework, which is general enough to model a wide range of cyber-physical systems, and taking advantage of the Robot Operating System (ROS) [37, 38] – an open-source meta-operating system that provides a message passing structure between different processes (or nodes) across a network (inter-process communication) – researchers at the University of Pennsylvania have developed a modular programming environment for robotic applications called ROSLab [11].

ROSLab enables users to model an architecture of an application that consists of a set of computational nodes and communication channels between them. The interfaces of some commonly used nodes such as sensor and actuator nodes are pre-defined in ROSLab. Users can define a new node and its interface by selecting the channels to add to the interface of the node and automatically generate "skeleton" code. While ROS was the initial target platform for ROSLab, the back-end code generation can easily be adapted for other platforms. Fig. 10 shows an example of the implementation of ROSLab for the creation of a ROS node that receives a joystick input and sends throttle outputs to a ground vehicle. Each block dragged and dropped in the ROSLab workspace is characterized by specific interfaces that contain information such as frequency of operation, measurements variance, and jitter.

4.2 Co-design of hardware mechanical components.

Recent work extended ROSLab to provide a design environment for creating mechanical components of robots [39]. This work incorporated a component library of pre-designed parametrized robotic building blocks into ROSLab. In this interface, desired blocks can be dragged into a workspace, and parameters can be set by the user based on target specifications. Exposed interfaces on each robot component are represented by ports on the ROSLab block; these ports can be wired together to specify electromechanical connections.

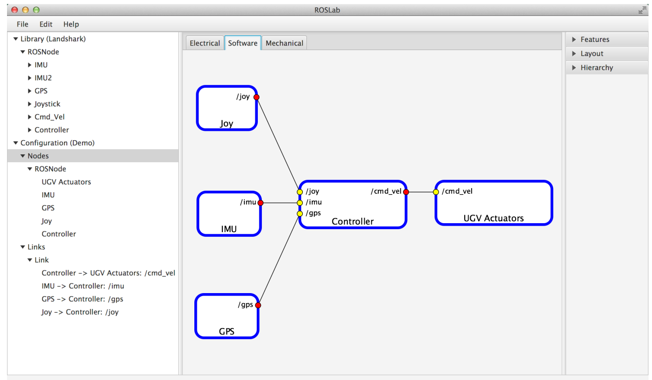


Fig. 10. ROSLab environment: example of creation of a high-level software skeleton code for controlling a ground vehicle via joystick [11]. Demonstrations available at `http://www.seas.upenn.edu/~nicbezzo/ROSLab.html`.

Assemblies of these blocks can be saved as components in the library to be used in future, higher-order designs. In this way, a full robot can be hierarchically composed from its constituent blocks. Once a robot has been designed, it can be compiled to generate manufacturing specifications. Fig. 11 shows a design example for the development of a simple two-wheeled robot which can be specified as two motors sides ("Right Half Seg" and "Left Half Seg" in Fig. 11) attached to a central core ("Seg Brain" in Fig. 11). To add stability, a third point of contact, such as a tail, can be added to a free end. Symbolically, this is represented by the following relation:

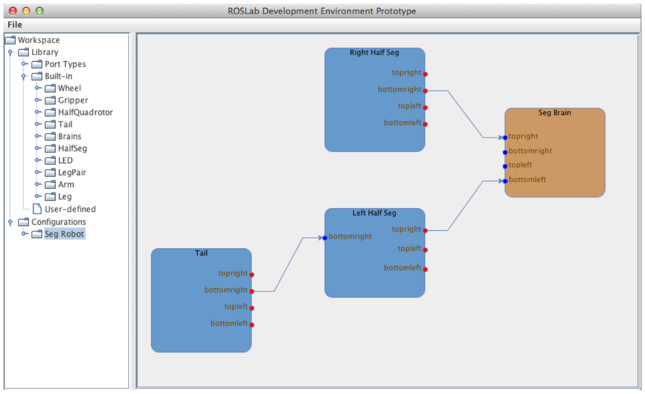
$$Seg = leftwheel + core + rightwheel + tail \qquad (1)$$

The overall vision is to be able to extract dynamic and kinematical models from the mechanical model developed though ROSLab. Physical parameters such as the dimension, weight, and moment of inertia could be extracted from the designed system and then passed to a mathematical control system representation to create a more accurate model of the plant.

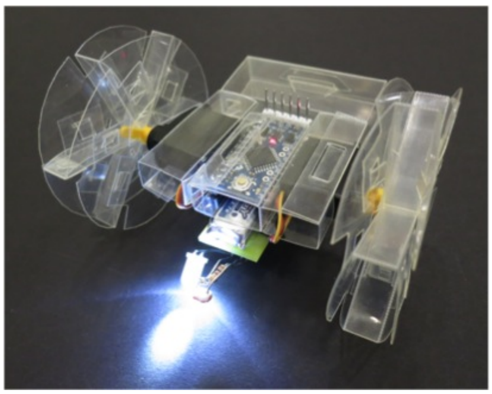
Another tool already mentioned in Section 3.1 is popupCAD [33], a design environment which facilitates the development of laminate devices, pop-up mechanisms, and flat-foldable structures. This design suite is implemented in Python and QT and has the ability to create and perform operations on two-dimensional geometric primitives. The tool allows the sketching of lines, polygons, circles, as well as the extraction of information from Solidworks, the definition of bodies and joints, all taking into consideratino the manufacturing process. Fig. 12 shows a snapshot of the popupCAD for the development of a laminate device.

4.3 Cogeneration of electrical and software Designs

From an electronic perspective two main cogeneration philosophies are available: i) a modular approach vs. ii) an embedded generation of printed circuit boards (PCBs).



(a) A simple two wheeled robot design



(b) The resulting robot

Fig. 11. A Seg robot designed within the ROSLab programming environment and fabricated in a cut-and-fold process [39]

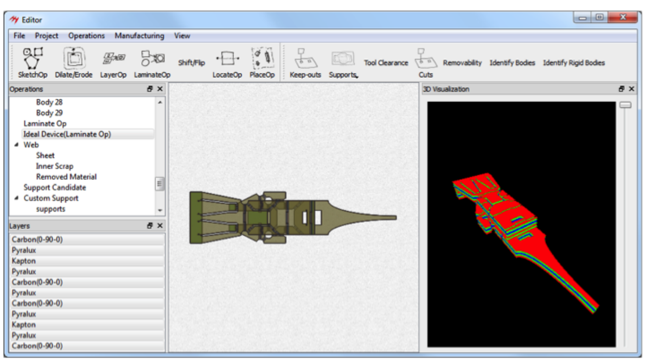


Fig. 12. The popupCAD environment [33]

Both approaches have their advantages and disadvantages. The circuits created with modular specifications have the advantage that are reusable, well-tested, task-specific, and well supported by the Arduino [40] and Sparkfun [41] community. However electronic modules have also disadvantages. They are larger in volume and mass compared to dedicated boards as they must accommodate large numbers of connectors, many of which go unused and are generally unreliable. Modules also have an increased cost over the raw parts associated with supporting the module manufacturer. Embedded PCBs on the other hand have the big advantage that can be optimized and reduce the overall size and weight of the final board which are critical factors when building small print-and-fold robots as discussed in this work.

In [42] the authors who developed ROSLab, introduce the EMLab environment for the rapid co-design of embedded PCBs (Fig. 13). The tool uses a similar drag-and-drop graphical interface like ROSLab in which electromechanical components are represented as blocks connected together on a workspace to describe a PCB design. The tool takes advantage of a library of electromechanical components schematics called *eocsystem* created a priori by expert developers that contain the pin specifications associated to each component and their software function. Within the UI, the ecosystem libraries are loaded, automatically parsed by the EMLab tool, to create a simplified library of nodes. Underneath this simplified interface, all information about the functionality of each pin for every component are still available, but hidden to the user. Finally a pin-matching algorithm followed by verification framework, build all connections to realize a EAGLE [43] schematic (Fig. 14).

Fig. 13 shows a snapshot of EMLab with all necessary nodes for the design of a segway PCB. Fig. 14 shows the generated schematic and manufactured PCB and finally Fig.15 displays the final segway robot with the PCB created from EMLab.

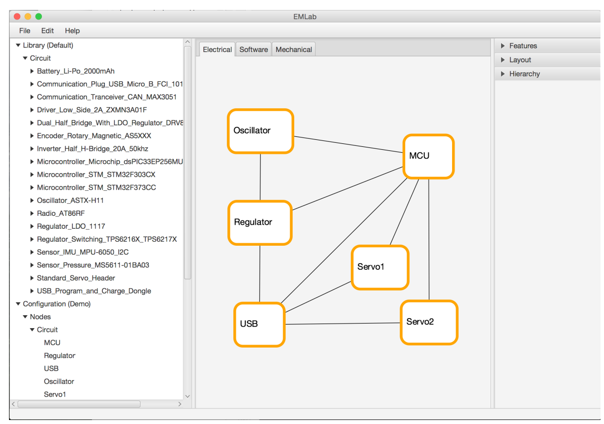
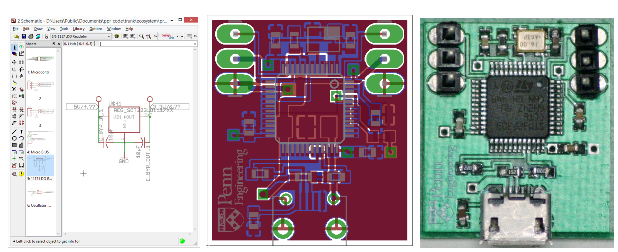


Fig. 13. The design of a segway PCB in EMLab.



(a) (b) (c)

Fig. 14. The generated EMLab schematic in EAGLE (a), placed and routed board in EAGLE (b) and final fabricated PCB (c).

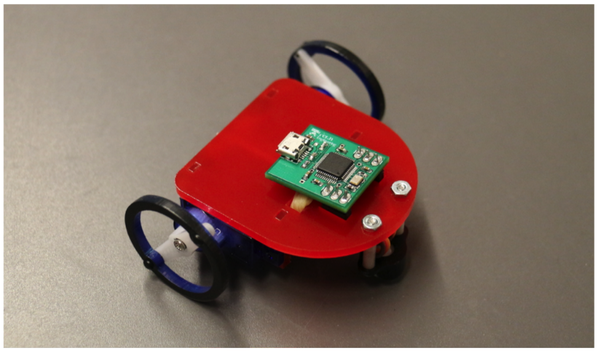


Fig. 15. The final mini segway created from EMLab

Standing more from a modular implementation, in [9] the authors propose a modularized approach to facilitate automatic composition of electrical devices. Specifically, the authors developed a generic module which features a microcontroller and three general-purpose ports for connecting devices such as servos, LEDs, or sensors, and two connections for communication with other modules (Fig. 16). Devices can be attached to the module and modules can be chained together, but the code on the microcontroller does not need to change based on the configuration of attached devices.

Fig. 16. Plug-and-play modules have ports for attaching devices and can communicate in chains. They serve as interfaces between devices and the main controller, simplifying wiring and facilitating automated layout [9].

In addition to the physical configuration, a library of software components was developed to support both low-level control and user interaction. This library hides implementation details from the user, such as the need to interface with microcontroller. Each device is assigned a virtual pin number which can be used to reference the device, and the user can simply imagine a large microcontroller with all devices attached directly to its virtual pins. This allows an intermediate user to write higher level code using the automatically generated code library.

Fig. 17 shows an example using this system along with the modular composition of mechanical building blocks to design a robotic arm. The user connects blocks for hinges, beams, and a gripper, folds the generated cutout, follows the generated instructions for plugging in the electrical devices, and immediately controls the arm with the associated Android app via Bluetooth.

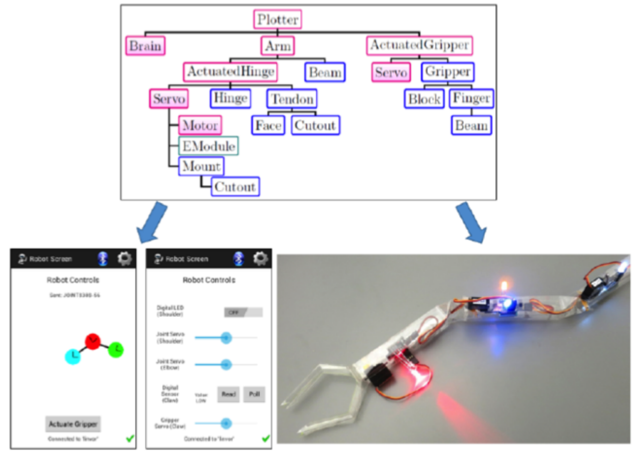


Fig. 17. A robotic arm is generated using the integrated electromechanical design library. The user specifies the structure by attaching blocks hierarchically, and the system generates the electrical layout (here, including three generic modules), a user interface, and fabrication files [9].

5 Discussion

NB: still working on this section In this paper we have described a series of techniques, technologies, tools, and recent results on rapid prototyping and fabrication of robotic systems. We conclude this work with a discussion on the challenges and future steps on this area of study.

5.1 Verification and Validation

The fabrication techniques and software tools reviewed in this paper allow for the rapid prototyping of robotic systems, however the final product doesn't always conform to the design specification, may be unfeasible, or may not be capable of performing the desired task. Thus it is necessary to consider verification and validation to ensure that the developed design satisfies the designer requirements.

Specifically, verification confirms that the system properly reflects the requirements specified for it (i.e. ensuring that the system was "built correctly"). Verification is matching the physical output of a manufacturing process to the fabrication and structural specifications. On the other hand, validation confirms that the system, as provided, will fulfill its intended use, ensuring that "we built the right tool" for the intended mission. This translates into matching functional specifications against structural and fabrication specifications. Typical inputs are requirements (e.g., mission time, number of goals, energy consumption constraints, etc.), design representations, and specifications (e.g., number and type of agents, control and performance quality, etc.), dynamical and kinematical models, and software code. Typical outputs are a determination of whether the design components or the entire systems meet the requirements, description of failure modes, and recommendation for design improvement. For example, in [42] the authors use a Satisfiability Modulo Theories (SMT) solver to check that both voltage and current are within desired thresholds to guarantee a correct functioning of the PCB generated by the EMLab environment.

There is an interesting trade-off between verification and validation. The proliferation of 3D printer systems greatly reduce the need for validation of structural designs: without the high startup investments of traditional manufacturing technologies, it becomes possible and sometimes even economical to adopt a "trial-and-error" approach to manufacturing, printing many iterations of a design until the right output is attained. However, this approach only became possible after a concerted effort to specify the verification of such manufacturing devices. Additionally, different robotic applications may place different requirements on verification and validation standards, but nonetheless, both are necessary to some degree, and more is always better.

5.2 The role of robotic design-on-demand

The robotics community is usually divided in opinion when it comes to the value of designing custom robots. Some advocate creating design systems to enable users to develop their own robots. On the other hand, others feel that is unnecessary, instead recommending focusing on expanding the capabilities of robot manufacturing processes to allowing for more general purpose robots.

There is a general agreement that there will be a broad range of tasks that a robot might be called upon to perform. Whether that is achieved by a custom robot designed specifically for that single task or a general purpose robot that can perform that task in addition to many others, the importance is that it gets done. Both approaches have their costs and benefits, and at this stage it is hard to conclusively determine whether either is objectively better.

The technologies described in this paper will enable both customized and general purpose mass produced robotic systems. Choosing one or the other category will depend on the type of research and applications one wants to focus to. Control engineers that are interested in developing motion planning strategies with stable and robust controllers will be more likely interested in using a general purpose robot to focus on the software level control specifications. On the other hand researchers that are working in kinematics and dynamics, will be more interested in quickly developing different platforms changing their mechanical and electronic specifications. The same applies for material scientists and in general mechanical engineers. Software engineers concerned with verification and code level analysis can benefit from tools like ROSLab since it can provide a systematic way to generate provably correct codes. Finally, beginner users like high schoolers, college freshmen, and hobbyists will benefit from these technologies to create on demand platforms for academic or personal use.

An enormous advantage of rapid prototyping is that it can considerably lower the manufacturing cost. Commonly sold robotic systems like UGVs, UAVs, and medical robotic systems can have prohibitive costs especially to enable large scale systems research development like swarming of multi-agent heterogeneous and homogeneous robotic systems. Thus the rise of rapid prototyping and co-design technologies will allow to push the research towards different horizons and build a larger robotics community. ...(need to rephrase)

5.3 Robots in human lives

With the applications of robotic research occasionally veering off into unforeseen directions (such as for artistic endeavors), a question that comes to mind is whether robots can go to positively impact humanity. We can identify agriculture and field robotics as well as custom orthotics and robotic healthcare as fields where robotic development has potential to greatly improve human lives. For instance, 3D printing technologies have recently demonstrated that are well capable of generating prostheses at low cost [44]. Similarly, soft robotics, could take advantage of their ability to maneuver through small spaces and their rubbery appendages to be employed in delicate surgical operations and reduce the likelihood of surgical damage.

Last, but not least, the type of rapid prototyping and programming techniques presented in this work will have an enormous impact in education: low cost, accessible, and easy to develop robotics will propagate to all levels of education, encouraging the next generation of roboticists. In this particular case, origami cut-and-fold robotics and simplified and intuitive GUI based co-design tools like ROSLab, popupCAD, and EMlab could help reducing the overall learning curve time for programming, controls, mechanical, and circuit design (...need to rephrase this).

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