Rapid Fabrication of Non-Assembly Robotic Systems with Embedded Components

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ABSTRACT

In this paper, the application of Rapid Prototyping in fabricating non-assembly robotic systems with inserts is presented. Previous work demonstrated the use of the Rapid Prototype Stereolithography and Selective Laser Sintering techniques to fabricate prototypes of mechanical mobile joints. As examples of their applicability, the joint designs were then used to fabricate complex multi-articulated, multi-link, multi-loop systems in one step, without requiring assembly while maintaining the joint desired mobility. Expanding upon this, current research explores methods of insertion of component parts during the rapid prototype process. The Rapidly Prototyped Mobile Observation Vehicle (RP MOVe), was fabricated to demonstrate this method and is presented here.

KEYWORDS

Rapid Prototyping, Stereolithography, Robotics, Inserts, Non-Assembly.

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1 INTRODUCTION

It is well known that current techniques for robot design and manufacturing are extremely time consuming procedures. It can take well over a year to design, prototype, test and deploy a robotic system. In many cases, such as flexible manufacturing, space, military and medical industries and field missions, such time frames are not acceptable because immediate action needs to be taken to perform a specific task. Current solutions to the problem of rapidly deploying robotic systems include either the use of off-the-shelf general robots or the use of modular systems that can be reconfigured from a small number of reusable modules. Both solutions have disadvantages. Off-the-shelf robots are very expensive, considerably larger in size and weight than it is required by the specific task, and they possess redundant components that not all of them are needed for specific robot tasks. In addition, in small scales, off-the-shelve robotic systems are inexistent. While modular robots offer robot reconfigurability in a short time, their modules are heavy, cumbersome and complex, requiring long fabrication times. If a specific task requires different module type or dimensions it is impossible to fabricate the modules in a very short time. An alternative solution to the problem of developing low cost, rapidly deployable, task specific robotic systems is to use Rapid Prototyping techniques.

There is an important economic, industrial and societal (e.g. medical applications, space exploration and catastrophe site search and cleanup) need to decrease considerably robot and other mechatronic machine design, fabrication and deployment times from months and years to just a few hours and days from the moment of conception to the moment of deployment. Having a software and hardware system that will be able to rapidly and automatically design and fabricate robotic devices and other complex machines will benefit tremendously our economy and our remote intervention capabilities. Robots and complex machines produced in this way will be designed specifically for a task and thus their cost, size and performance will be optimized. Further cost reduction could be achieved
through the recycling of the robot components. Industrial environments will be able to be reconfigured into new and completely different product lines without purchasing new machinery. Remote world colonization such as space or underwater could be achieved by onsite rapid machine design and fabrication avoiding the cost and difficulties of transportation. On a more philosophical level, having an intelligent machine that can rapidly create and fabricate another intelligent machine, opens a completely new multi-disciplinary field of study: machine and robot reproduction. Using current software and hardware technology, nowadays it is possible to develop such machine and robot reproductive hardware and software system. The broader goal of this project is to bring together these technologies and establish design and prototyping foundations and paradigms for machine and robot reproduction systems and their "children": the rapidly developed robots and machines.

We envision a futuristic robotized design and fabrication workstation for rapidly deploying robotic systems, shown schematically in Figure 1. This system will include a high performance computer with CAD software, connected directly to a robotized rapid prototyping system. The term robotized is used here to denote that the rapid prototyping machine will itself be a robot that will be able to manipulate parts and insert them at specific locations on the fabricated robot structure. The engineer will specify the task to be performed and general desired characteristics of the robot. Then, automated CAD software coupled with advanced evolutionary design algorithms will calculate an optimal design for the robot. The final robot design will be fabricated immediately in the rapid prototyping system. The robotic system will be fabricated in a one step procedure with no assembly required and with all electromechanical components, including structural elements, joints, actuators, sensors, computers and other robot components inserted automatically during fabrication.
One of the steps for making the above futuristic view for the rapid and automatic design and fabrication of robotic systems a reality is to study the application of current Rapid Prototyping techniques in the design and fabrication of robotic systems. The advantages of using Rapid Prototyping techniques in robot design and fabrication are numerous. With Rapid Prototyping techniques, physical robot prototypes can be obtained in a very short time, thus making quick design evaluation possible. By using these physical prototypes, several properties of the robotic systems can be evaluated immediately such as: a) workspace evaluation, b) identification of singular configurations including uncertain configurations where the robotic mechanism has internal mobility, c) determination of link interference, and d) visualization of joint limits. Evaluating these fundamental properties of the Rapid Prototyped robotic mechanism can considerably reduce the time and improve the quality of the design process. In addition, Rapid Prototyping allows the fabrication of complex three-dimensional structures, which could not be produced with conventional fabrication processes. This has made it easier to incorporate and attach sensors, actuators and transmission elements within the structure and joints of the robotic system. Furthermore, Rapid Prototyping permits one-step fabrication of multi-articulated, multi-link systems as a whole, without requiring assembly of their structural members and joints after fabrication. These systems are called in this work non-assemblage robotic systems. Finally, the addition of components during the building phase to this one step fabrication technique can provide rapid production of fully functional and mobile robotic systems, and offers an alternative manufacturing process.

Robotic systems have been used as part of a Rapid Prototyping process [1, 2]. However, the application of Rapid Prototyping in robot and mechanism design and fabrication has been very limited. Professor Gosselin and his group at Laval University, using a Fused Deposition Modeling Rapid Prototyping machine, fabricated several mechanisms such as a six-legged six degree-of-freedom par-
allel manipulator [3, 4, 5]. These rapidly manufactured mechanisms required assembly after Rapid Prototyping of the mechanism parts. Professor Cutkosky and his group at Stanford University using a different Rapid Prototyping process called Shape Deposition Manufacturing developed planar, non-assembly mechanisms and robotic systems with embedded sensors and actuators [6, 7]. These components were inserted in the multi-articulated structure during its fabrication as opposed to their integration in post-fabrication assembly phases. This group also proposed methods for performing the systematic design, error analysis and optimal pose selection for these mechanisms [8-11]. Additionally, researchers at the Georgia Institute of Technology, proposed methods to develop complex devices with embedded components using the Stereolithography technique [12, 13].

The idea of developing robot reproduction systems has been expressed by robot futurists and evolutionary roboticists [14, 15]. Recently, Prof. Pollack and his group at Brandeis University developed a complete prototype for automated design and fabrication of robotic systems [16]. They have used evolutionary computations to calculate an optimal robot design and a 3D-Printing rapid prototyping machine to fabricate the robot. While their computational method was very powerful, they only considered a very small number of modules (4 types) and thus the developed robotic systems were very simple.

Our group at Rutgers University has studied the fabrication of non-assembly robotic systems using two different Rapid Prototyping processes: Stereolithography (SL) and Selective Laser Sintering (SLS). Results of our work have been extensively presented in [17-20]. It is suggested to those who desire the details of part tolerances, and build and processing procedures for the non-assembly mechanisms, to please read these references, specifically [20], as only a brief review is given here. To the authors’ knowledge, this was the first successful fabrication of multi-joint, multi degree-of-
freedom, spatial robotic systems and mechanisms without requiring any assembly using the SL and SLS processes.

Over the past three years, several non-assembly mechanisms and robotic systems have been developed, all beginning with the production of the joints to assure mobility. The methodology of: 1) specifying joint clearance, 2) defining build direction, 3) utilization of support structures, and 4) developing novel design strategies, all provide the basis for this type of mobile, non-assembly technique. An example of this research is shown in Figure 2, where different types of mechanical joints, such as revolute, spherical, prismatic and universal, were fabricated with the SLA 190. These joints were all produced without requiring assembly. See [20] for a detailed review of this process.

In the current project, the concept of non-assembly robotic systems is carried a step further, by incorporating component parts during the build process. Here component parts refers to items such as sensors, motors, bearings, gears, or even electronics, that would render the robotic system or mechanism a mobile functioning unit. This paper discusses some techniques for accomplishing this goal as well as present some examples, in particular, the Rapidly Prototyped Mobile Observation Vehicle (RP MOVe), that illustrate our findings.

2 RAPID PROTOTYPING

Rapid Prototyping or Layered Manufacturing is a fabrication technique where three-dimensional solid models are constructed layer upon layer by the fusion of material under computer control. This process generally consists of a substance, such as fluids, waxes, powders or laminates, which serves as the basis for model construction as well as sophisticated computer-automated equipment to control the processing techniques such as deposition, sintering, lasing, etc [21, 22]. Also referred to as Solid Freeform Fabrication, Rapid Prototyping complements existing conventional manu-
facturing methods of material removing and forming. It is widely used for the rapid fabrication of
dgphysical prototypes of functional parts, patterns for molds, medical prototypes such as implants, bones
and consumer products [23]. Its main advantage is early verification of product designs. Through
quick design and error elimination, Rapidly Prototyped parts show great cost savings over tradition-
ally prototyped parts in the total product life cycle [24]. Currently, there are over 30 different types of
Rapid Prototyping processes in existence, such as Stereolithography, which is used here and de-
scribed below.

Stereolithography (SL) is a three-dimensional building process, which produces a solid
plastic model. In this process, an ultraviolet (UV) laser traces two-dimensional cross-sections on
the surface of a photosensitive liquid plastic (resin). The laser partially cures the resin through
low energy absorption of laser light thus producing a solid. The first cross-sectional slice is built
on a depth-controlled platform, which is fully submerged under the first thin layer of resin. This
and each successive thin layer of liquid resin has a depth equal to that of the vertical slice thick-
ness of the part. After each slice is traced on the surface of resin, the platform lowers by a depth
equal to that of the slice thickness. Successive 2-D slices are cured directly onto the previous
layer as the part is built from bottom to top.

Support structures are needed to maintain the structural integrity of the part and supports
overhangs, as well as provide a starting point for the overhangs and for successive layers on which to
be built. These supports are constructed from a fine lattice structure of cured resin. After the part is
fully built, the support structures are removed and the part is cleaned in a bath of solvent and air-dried.
The prepared parts are then flooded with high-intensity UV light in a Post-Cure Apparatus (PCA) to
fully cure the resin. The Department of Mechanical and Aerospace Engineering of Rutgers Univer-
sity is equipped with the Stereolithography machine model SLA 190, from 3D Systems, CA. Ciba-
tool® SL 5170 resin is used for all the parts, though other basis photo-polymer resin epoxies with various physical properties are available for this machine.

3 RP FABRICATION WITH INSERTS

Though intriguing, the concept of embedding parts during the rapid prototype process does present some challenges. Each RP method offers different challenges as well as advantages. For example, with SL there is the problem of laser shadowing once the part has been inserted [13]. One way to avoid this is to adjust the part orientation for the build. Other challenges that are more nonspecific to technique are determining: 1) component reaction to the basis material and/or post-processing, 2) tolerances between the embedded components and the build part, 3) whether to utilize or delete supporting structures, 4) build orientation, and 5) insertion points.

Due to prior research on articulated non-assembly mechanisms, our group had a basis for developing a method for finding the clearances, build orientation and support structure utilization associated with the SLA 190. Some initial experiments were completed to find the tolerances of various parts inserted during the build. Through a trial and error process, previously built SLA parts, and plastic and metal parts were inserted either before or during the build process to accomplish this task. The findings are shown in Table 1.

As a consequence of attempting to find the build clearances, the build orientation that is best suited for our machine was discovered. Prior to fabricating the entire RP MOVe, several parts were made in different orientations, requiring different parts to be embedded. To illustrate this, the experiment of building gears for the vehicle that is presented in the next section, is discussed here. This posed a unique problem in that the teeth of the gears needed to remain free
from attachment to the supports from the SL procedure. Therefore, the best orientation for the gear teeth is vertical, however the best orientation for the inserts is horizontal. Four gears were made (Figure 3); three with inserts and the fourth without. Two were embedded with a metal threaded insert and the third with a metal nut – necessary for later attachment to the axles of the vehicle. As can be seen from the test, the vertical gear shown in Figure 4a did not fuse due to shadowing, and the teeth of the horizontal gear in Figure 4b have extra material that prevents smooth movement and will require sanding. The gear in Figure 4c (top gear) with the embedded nut was the most successful build. This gear was made in the vertical position, which allowed for the most accurate fabrication of the gear teeth and was not a hindrance to insertion as the nut was totally immersed into a nearly complete part. The last gear (Figure 4c, shown on side) was used as the control model to verify that insertion of a part is more viable than non-insertion. In order to insert an item into the control gear additional machining would need to be done, and the radial clearance would have to be no larger than 0.175mm (0.0069in) for a tight fit. This requires more work and the tolerances are more critical.

These experiments illustrated that not only are tolerances, supporting structures, and build orientation factors, but also the type of insert. Additionally, here the support structures were a problem for the fabrication, but it has been shown in [20] that the SL supports can be used to one’s advantage. Supports can be drawn into the part where necessary to maintain the structural integrity and to avoid interference with the insertion. Furthermore, each fabricated part needs to be assessed individually for all these characteristics, which are often interdependent.

In addition to the above, experiments were completed to test the possibility of inserting sensitive components, such as motors, during the build cycle. To accomplish this task, one
motor for the RP MOVe (see next section) was used. First a box that fit the motor tightly was fabricated. Once this box was clean and dry, the motor was inserted (Figure 5) and sealed inside. Since the motor shaft and the wires extended from the box, clay was packed around any openings to assure that resin did not leak into the motor. There was an additional concern of leakage during the cleaning process; the clay prevented this as well. The final step was inserting the encased motor into another box during the build process. This was accomplished by placing the entire motor with the wires into the box and later pulling the wires through holes in the box to attach to the batteries (Figure 6). This box also has a moveable lid, so that this could in turn be sealed and inserted into another item. This process was successful in providing a viable means of inserting sensitive sealed parts during fabrication, as well as testing tolerances for the hinge and the encased motor.

From all these experiments a basic insertion procedure was developed. In particular, the proper insertion point was determined by dividing the height (the distance from the platform to the proposed layer of part introduction) by the layer thickness, plus one (1) since the machine begins count at layer one:

\[
\text{Insert Level} = \frac{\text{height}}{\text{layer thickness}} + 1
\]

This is more reliable and predictable than depending upon time of insertion. It’s difficult to ensure the proper addition of all the various phase times such as pre-dip, z-wait, analyzing, and drawing. Furthermore, it’s helpful to have enough time for the proper placement of the component into the part being fabricated. This is accomplished by either stopping the machine (not recommended) or by adjusting the z-wait time length at not only the desired layer, but at the
previous and successive layers. In summary, the key points to consider for inserting component parts are as follows:

1. Correct clearance for part/component types.
2. Proper build orientation.
3. Utilization of support structures.
4. Appropriate selection of components to be embedded.
5. Protection or preparation of sensitive parts to be inserted.
6. Calculation of the right insertion layer level.
7. Suitable adjustment of the z-wait time.

4 DEMONSTRATION EXAMPLE: RP MOVE

The procedure described in the previous section, was tested in the fabrication of the RP MOVe (Figure 7). This radio-controlled vehicle is a combination of inserted and electrical components. The inserted parts, two axles and a dog bone shaft (Figure 8), are mainly used for the movement of the vehicle. One of the axles is attached to the tire and the other is attached to a gear (Figure 4b), while the dog bone shaft links the two axles together. This set up transfers the rotational power from the motor to the tire. The electrical components consist of two motors, two speed controllers, a receiver, a camera power voltage regulator, and a camera. This rapidly prototyped vehicle was built in several phases, beginning with the chassis. During the fabrication of the chassis the axles and bearing cases, and the “dog bone” shafts were inserted (Figures 9 and 10).

The complete chassis was built in a vertical position and took approximately 80 hours to build. Supporting structures were added to reinforce the overhangs and some of the default
structures were deleted, both measures to accommodate the insertion process. The complex geometry involved in this part illustrates a benefit of rapid prototyping techniques. Moreover, it would have been difficult to build this part had the above-mentioned components not been inserted during the build. Figure 9 shows the rear axle completely embedded in the chassis. This was necessary to provide support and stability to the part when the vehicle is in use. The technique of inserting during the build process made this possible and illustrates the benefit of this procedure, without which the design goals could not have been accomplished.

The vehicle top, camera stand, motor cases, and gears were all fabricated and added post build (Figures 11 and 12). Note that for RP MOVe final fabrication, the motors were not inserted during the building phase; rather they were placed in the custom designed motor cases (Figure 11) and snapped into place on the chassis with the other post-build assembled parts. While it is a given that mechanisms can be constructed after rapid prototyping, this project offers an example of an alternative fabrication solution for difficult or more interesting assemblies. This combination of insertion and non-insertion steps demonstrates the flexibility of RP manufacturing.

Figure 13 shows the complete fabricated and assembled vehicle. The vehicle weighs 1.81 kgs (4 lbs) without the camera and approximately 2.27 kgs (5 lbs) with the camera. It has been tested to climb an incline of 12° and has a speed of approximately 23 cm/s. The RP MOVe vehicle was successful in showing that mechanical parts can be inserted during the rapid prototype process.
5 CONCLUSIONS

Rapid Prototyping has been shown to be a viable means of simple and quick fabrication of prototypes for the articulated structures of robotic systems. Additionally, the successful fabrication of the RP MOVe illustrates the use of rapid prototyping as a means of manufacturing in which component parts are added during the build process. Both of these techniques combined, provide a means of developing Rapid Prototyped fully functioning non-assembly type robotic systems and mechanisms with embedded component parts.

While the methods described here do provide an alternative manufacturing technique that can be beneficial to those who desire a fully-functioning, multi-articulated mechanism with embedded components, it is important to note that the experiments to date have been performed using the SLA 190. The general process described can be modified for other RP machines, though the process may not be as easily accomplished. For example, in [12, 13] the SLA 250 was adapted to achieve their research goals. Future investigations will include the use of the Stratasys, Inc. FDM Titan and the 3D Systems Viper machines.

6 ACKNOWLEDGMENTS

This project is supported by a CAREER grant (DMI-9984051) from the National Science Foundation. Furthermore, this material is based upon work supported under a National Science Foundation Graduate Research Fellowship (recipient Kathryn J. De Laurentis). Any opinions, findings, conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation.
REFERENCES


LIST OF TABLES

Table 1. Clearances Between Various Parts Inserted During the Build

LIST OF FIGURES

Figure 1. Artist's View of a Robotized Design and Fabrication Workstation for Rapidly Deploying Robotic Systems.

Figure 2. Stereolithography Joint Fabrications

Figure 3. Four Gears with Different Inserts (Control gear without insert – first on left)

Figure 4. Individual Views of Various Embedded Objects into the Gears

Figure 5. Motor Inserted Inside Case

Figure 6. Encased Motor Inserted Into Box

Figure 7. CAD Drawing of RP MOVe

Figure 8. Axles with bearings and Dog Bone Shafts

Figure 9. Close-up of Embedded Rear Axle

Figure 10. Complete Chassis with Inserts

Figure 11. Chassis with all added Components

Figure 12. RP MOVe Without the Cover

Figure 13. Assembled RP MOVe
**Table 1.** Clearances Between Various Parts Inserted During the Build

<table>
<thead>
<tr>
<th>Types of materials</th>
<th>Flat surface (mm)</th>
<th>Radial surface (mm)</th>
<th>Flat surface (inch)</th>
<th>Radial surface (inch)</th>
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<tr>
<td>Resin parts with resin parts</td>
<td>0.30</td>
<td>0.50</td>
<td>0.01182</td>
<td>0.019685</td>
</tr>
<tr>
<td>Other parts with resin parts</td>
<td>0.15</td>
<td>0.20</td>
<td>0.00591</td>
<td>0.007874</td>
</tr>
</tbody>
</table>

Note: “Other parts” refers to metal or plastic objects
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Figure 3. Four Gears with Different Inserts (Control gear without insert – first on left)
Figure 4. Individual Views of Various Embedded Objects into the Gears
Figure 5. Motor Inserted Inside Case
Figure 6. Encased Motor Inserted Into Box
Figure 7. CAD Drawing of RP MOVe
Figure 8. Axles with bearings and Dog Bone Shafts
Figure 9. Close-up of Embedded Rear Axle
Figure 10. Complete Chassis with Inserts
Figure 11. Chassis with all added Components
Figure 12. RP MOVe Without the Cover
Figure 13. Assembled RP MOVe