

**Towards a New Manufacturing Approach to Realizing Bio-Inspired Robots
with Mesoscale Features**

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1. Introduction

Bio-inspired robots derive inspiration in their shape, structure, and functionality from biological creatures. Many biological creatures such as birds, insects, and other animals have been identified to have capabilities which can be utilized in operations such as search, rescue, recovery, surveillance, sensing, maintenance, and ordinance disposal. Small animals, insects, and birds are an attractive source of inspiration in such applications due to their agility and stealth characteristics.

Multifunctional structures have emerged as a useful concept for realizing high performance robots in highly demanding environments with many different requirements. To realize small robots, multifunctional structures with miniature features are needed. Cost-effective and high-throughput manufacturing of these multifunctional structures remains a challenge because of the delicate nature of miniature features. Traditional macroscale assembly-based approaches impose restrictions on the size and geometric complexity of multi-material interfaces, which leads to suboptimal solutions. Assembling components with miniature features require expensive robotic systems or time-consuming manual assembly under a microscope. On the other hand, more complex geometries can be realized through self assembly, but is not cost-effective for the size scales that go beyond the microscale. Hence, we need a new manufacturing method for realizing multifunctional structures with miniature features at the mesoscale.

Recent advances in mold manufacturing technologies (e.g., micro electro discharge machining) provide a way to economically mold polymeric components with geometrically-complex miniature features. Furthermore, it is also possible to use multi-material molding to create polymer structures with materials that vary in different portions. These advances have fundamentally changed how packaging for tools and many automotive components are currently designed and produced. Therefore, we envision that by combining recent advances in multi-material and miniature molding, we can create a new assembly-free manufacturing process to enable economically viable fabrication of multifunctional structures with miniature features for robotics applications. Using multi-material molding will eliminate the need for post-molding assembly and hence significantly lower the part count, while miniature molding technology will allow us to scale down feature sizes to economically manufacture multifunctional structures.

Scaling down the dimensions of a product typically does not mean the loads will also scale down, which results in increased thermal and mechanical stress on miniature features making them more delicate. Thus, unfilled polymers have too low of a Young's moduli, tensile strength, and thermal conductivity. For these reasons, miniature unfilled polymer parts deform too easily and experience significant thermal softening in the vicinity of heat generating elements (e.g., SMA wire actuators). In many applications, such as miniature robotic manipulators, only a limited level of scaling can be achieved using unfilled polymers. Recently developed polymer formulations with different concentrations and sizes of particle fillers (i.e., filled polymers) exhibit significantly improved mechanical properties (e.g., greater Young modulus and tensile strength) and thermal conductivities. For example a carbon fiber-filled Nylon 12 available from PolyOne, known as NJ-6000 TC, has up to 2.6 times higher tensile strength, 20 times higher Young's modulus and 50 times higher thermal conductivity compared to unfilled Nylon 12. For example, we used NJ-6000 TC to create a motor bracket for a miniature robot application. This bracket enables us to keep the motor at significant lower temperature during operation compared to using unfilled Nylon 12. Using filled polymers, it is possible to realize multifunctional structures with appropriate mechanical and thermal properties. However, filled polymers pose

many processing challenges for multi-material molding of miniature structures because of their high viscosity, cooling rates, and particle sizes that are within an order of magnitude of the miniature structure.

Currently, realizing a truly bio-inspired robot in the size scales of 5mm and 100mm is very challenging. This size scale is too big for micro-fabrication and poses significant challenges for traditional manufacturing processes. Hence, new manufacturing processes are needed for realizing truly bio-inspired robots in this size range. This presentation will introduce our research in assembly technologies and their application in the design and fabrication of bio-inspired robots.

As a part of previous work, we have used multi-material molding at the macroscale to create joints where premolded components of one material type act as tooling during subsequent molding stages to establish relative position and orientation between components in the joint. Unlike traditional objects consisting of many single-material components assembled via some form of standard fastening technique, multi-material assemblies come out of molds pre-assembled after the in-mold assembly process. This allows for significant reduction in part count and eliminates several assembly operations thus improving the overall productivity. Furthermore, it permits fabrication of geometries that could never be assembled due to interference fits. Figure 1 shows representative examples of such joints developed in our Advanced Manufacturing Lab at the University of Maryland.

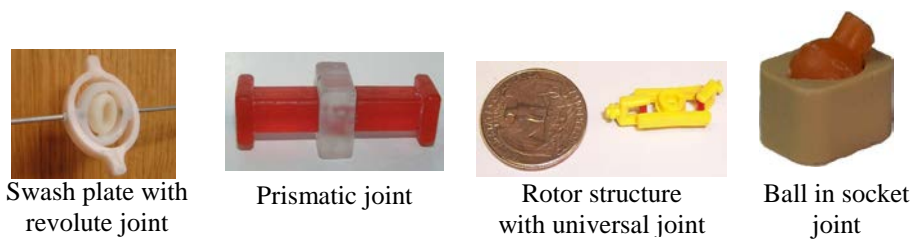


Figure 1: Miniature joints developed at UMD AM Lab using in-mold assembly

2. Mesoscale In-Mold Assembly

The in-mold assembly process eliminates post fabrication assembly and hence a large number of mesoscale joints can be easily realized. Material is assembled in the liquid form during the in-mold assembly and hence bio-inspired shapes that would have been otherwise impossible to realize are possible.

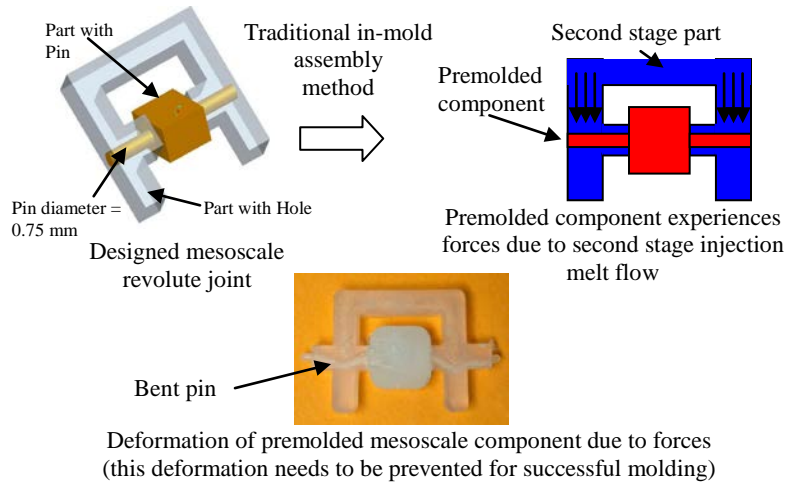


Figure 2: The plastic deformation of premolded component during in-mold assembly poses significant challenges at the smaller length scales

In-mold assembly poses new challenges for multifunctional structures due to reduced structural rigidity of the miniature premolded component. One of the major challenges that need to be addressed is minimizing plastic deformation of the premolded component during the second stage injection (see Figure 2). To address this challenge, we have developed the following two mold design strategies and detailed modeling approach to characterize and control this deformation.

- One cause of plastic deformation is the flow of the second stage polymer melt around mesoscale premolded components. To the best of our knowledge, we were the first to demonstrate a mold design with varying cavity shape for manufacturing a mesoscale multi-material revolute joint, illustrated in Figure 3. As part of this effort, we developed a model to estimate the effective pressure experienced by the premolded mesoscale part which falls in the flow path of an injection molding melt. We used a non-Newtonian flow CFD model to estimate this pressure within an error margin of up to 20%. This model is the first attempt at understanding the physics of interaction between the melt flow and free-standing structures in multi-shot molding processes, and suggests a non-intuitive influence of the mold geometry on the loading experienced by the free-standing structure. We also described a nonlinear FEA model for predicting the deformation of a mesoscale core when placed in the polymer flow environment. This model agrees with the experimental deformation with an error of around $\pm 2\%$. The deformation of the mesoscale premolded component was controlled through the radial support length to ensure the joint was capable of rotation.

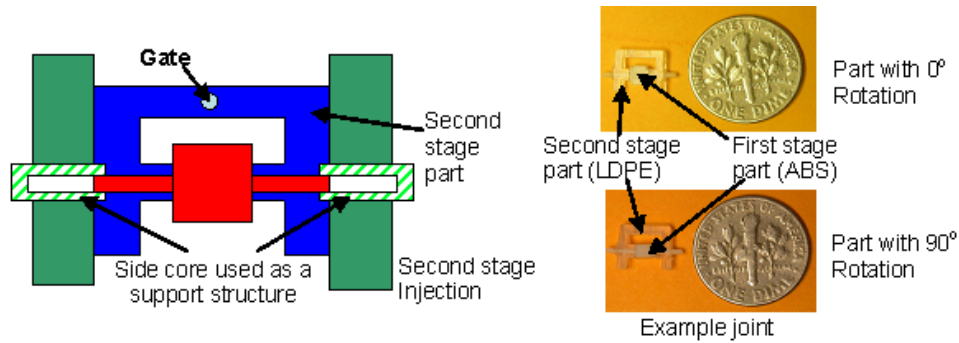


Figure 3: Mold design involving radial support part constraining feature to prevent deformation of premolded part for multi-material molding

- Another strategy we have developed for minimizing plastic deformation is to introduce of an opposing force to neutralize the drag force applied on the premolded component. As part of this work we reported an alternate mold design solution. This is illustrated in Figure 4. The force caused by the flow of the second stage polymer melt is fully neutralized if the gates are placed exactly equidistant to the mesoscale premolded component. However, it is important to understand the effect of misalignment in the gate placement on the plastic deformation of the premolded component in order to understand the parameters controlling manufacturing tolerances. As part of this work, we developed a computational model to predict plastic deformation of mesoscale premolded components resulting from the bi-directional filling strategy. Along with developing different mold design templates for manufacturing in-mold assembled revolute joints at the mesoscale, we have also developed methods to control joint dimensions.

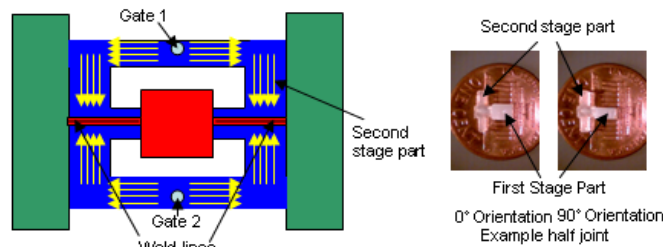


Figure 4: Mold design involving bi-directional filling to balance forces on the premolded component to prevent deformation

3. Mesoscale Insert Molding

Another possible process to manufacture in-mold assembled revolute joints is using insert molding. This process involves use of cylindrical metallic mold pieces made of Brass or Aluminum as mold inserts. These metallic inserts serve as shut off surfaces between the mold cavities which form the different parts of the revolute joint. This shut off surface ensures that the molten plastic that is injected into the mold cavities don't fuse the two cavities together during the filling phase. Subsequently after cooling, the in-mold assembled revolute joint consisting of two plastic parts and the metallic insert is ejected from the mold cavity. However, it is necessary to understand the effect of the radial stresses that develop at the joint interface due shrinkage of

the polymer parts over the metallic inserts. We have developed analytical models to predict the radial stresses at the joint interface. These models can then be used to select the most appropriate material and dimensional parameters necessary to manufacture in-mold assembled revolute joints using insert molding at both the mesoscale and the macroscale.

4. In-Mold Assembled Finger-Inspired Robot

To demonstrate the capabilities of the mesoscale multi-material molding using unfilled polymers, we have conceptualized and fabricated a finger-inspired robot which can potentially be used for neurosurgery. The device, called MINIR, has a diameter of 0.36", consists of 6 DOF and is fabricated using mesoscale in-mold assembly methods with Shape Memory Alloy (SMA) wire actuators. Our prototype is shown in Figure 5.

As expected, the SMA-actuated MINIR prototype revealed thermal softening of the unfilled polymer and SMA wire interface. The SMA wire heats up when in operation and softens the unfilled polymer it is anchored in. We believe using thermally conductive filled polymers will overcome this issue and make embedding heat generating actuators in multifunctional structures possible. We have already created a similar structure that served as a protective housing for embedded components, and realized similar kinematic functions by anchoring actuators and forming integrated universal joints.



Figure 5: 6-DOF MINIR weighing 2.94 grams



Figure 6: Multifunctional drive mechanism design for an MAV

5. In-Mold Assembled Drive Mechanism for Flapping Wing MAV

To demonstrate the capabilities of the mesoscale molding using both unfilled and filled polymers, we have designed and fabricated a multi-material compliant drive mechanism for a flapping wing bird-inspired robot. The drive mechanism converts the rotary motion of a brushless motor to the flapping motion of the wings. The multi-material structure consists of

mesoscale flexible hinges assembled in-mold with the rigid mechanism links. The rigid elements were molded using glass fiber filled polymer to enhance the structural rigidity. Due to the fact that the materials used to create the rigid and compliant sections may not chemically bond during the in-mold assembly process, we have developed mesoscale interlocking strategies for a robust anchoring of the hinge in the rigid structure to ensure its integrity and ability to transfer loads. The MAV utilizing the compliant multi-material drive mechanism weighs 38g and is capable of remote-controlled indoor and outdoor flight with 33g payload (see Figure 6).

6. References

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