Towards Assembly Automation at Small Size Scales

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Assembly at Small Scale

• A large number of small parts need to be assembled in a small package
  – Assembly operations need to be performed in 3D space
  – Assembly operations need to manipulate small parts in a very tight space

• Weight and size are crucial
  – Layered packaging approaches cannot be used
  – Need to create sufficient room for energy storage

**CardioARM for Cardiac Surgery:**
Consists of 50 rigid cylindrical links

Photo courtesy: Biorobotics Lab, Carnegie Mellon University
Our Idea

• Competitive Manufacturing in US requires
  – Material choices
  – Shape and size complexity
  – Low lead time
  – High throughput rate
  – Reduced manual labor
  – Low environmental impact
In-Mold Assembly: A New manufacturing Approach

• Introduce multiple materials in the mold sequentially
  – Change mold cavity between different molding stages
• Perform assembly and fabrication inside the mold
  – Mold acts as fabrication tool and assembly device
• Eliminate post-molding assembly
  – Attractive in markets where labor cost is high

Presence of an already molded component fundamentally changes the thermomechanical characteristics of the mold in the molding process.
In-Mold Assembly (Cont.)

Old Design – Fabrication & Assembly

• Traditional manufacturing
  – Fabricate individual parts
  – Assemble parts to create products

• Difficulties
  – Complex assembly operations need to be done manually
  – Assembling small parts is very challenging

New Design – In-mold assembly

• Benefits of in-mold assembly
  – Eliminate assembly operations
  – Eliminate difficulty in assembling small parts
  – Reduce part count/unit cost
  – Lower cycle time
  – Improve joint quality

11 part assembly

5 part in-mold assembly

(Credit: Drs. Jayant Sirohi and Inderjit Chopra)
In-Mold Assembly Methods

Overmolding

First stage Injection
- Closing the mold
- Injection of material
- Opening the mold

After the first mold stage, the part has to be dismantled...

Second stage Injection
- Closing the mold
- Injection of material
- Opening the mold

...and has to be assembled into the mold of the second mold stage

The part has to be removed completely from the first mold and then assembled into the second mold.

Cavity shapes need to change during molding before injecting second stage

Morphing Cavity

Cavity shape after completing first stage

(a) moving a mold piece

Cavity shape before starting second stage

(b) removing partition

(c) changing a mold piece

Final part
In-Mold Assembled Joints

**Rigid Body Joints**
- Prismatic joint
- Revolute joints
- Spherical joint
- Rotor structure

- We have developed mold design templates for successfully realizing revolute, prismatic, spherical, and universal joints using in-mold assembly.
- We have developed methods to control shrinkage of the second stage part to provide the adequate joint clearances.

**Compliant Joints**
- Compliant Clip
- Compliant members

- We have developed mold design templates for realizing variety of 1 DOF and 2 DOF compliant joints using in-mold assembly.
- We have characterized the influence of interface geometry on the interface strength to optimize joint performance.


Use of In-Mold Assembly in Creating Embedded Electronics

- We used in-mold assembly process to successfully embed batteries, motors, and electronics in a multi-functional structure.
- We have shown that embedded electronics exhibits superior resistance to mechanical and thermal impacts.

Full circuitry embedded in polyurethane

Full circuitry embedded in ABS
Macroscale Assembly vs. Mesoscale Assembly

• Macroscale
  – Traditional manufacturing and assembly is feasible
  – In-mold assembly reduces part count
  – In-mold assembly will have cost advantage for larger batch sizes

• Mesoscale (parts between 0.25 mm to 5 mm)
  – Traditional manufacturing and assembly not possible for truly 3D assembly operations
  – In-mold assembly is the only solution without drastic part redesign
  – Definite cost advantage since cycle times are considerably lower and product possibilities extended
Realizing Polymer-Polymer Mesoscale Revolute Joints Using Two-Shot Molding
In-Mold Assembly: Challenges at Mesoscale

- Challenges at Mesoscale

  - Side Core
  - First stage Injection

  Second stage Injection Location

  - Bent pins due to second stage injection

  Example Defective Component

- Modeling Plastic Deformations

  - Second stage melt
  - Premolded component

  CFD analysis using FLUENT 6.3.26 for force modeling
  
  Structural analysis using ANSYS 11.0 for deformation modeling

  Distinction between macroscale and mesoscale from the In-mold Assembly perspective

Goals

• Identify defect modes unique to in-mold assembly at the mesoscale caused due to direct scaling down of macroscale molds
• Develop mold design solutions, to overcome defect modes that were identified
• Develop process models to characterize and control defects unique to mesoscale in-mold assembly
First Successful Demonstration

- Successful in-mold assembly of revolute joint with mesoscale features

- Pin dimensions
  - Modeled: **0.76 mm**
  - Molded: **0.71 mm**
  - Estimated Shrinkage: **6.6%**
  - Length: **2.5 mm**
In-Mold Assembly: Two Alternative Methods

- In-mold Assembly using Radial Supports
  - Side core used as a support structure
  - Second stage injection
  - First stage part (ABS)
  - Second stage part (LDPE)
  - Gate 1: 0° Orientation
  - Gate 2: 90° Orientation

- In-mold Assembly using Bi-directional filling
  - First stage part
  - Second stage injection
  - Gate 1 and Gate 2

Experimental vs. FE Analysis

![Graph showing deformation vs. radial support length](image)


• To best of our knowledge this was the first demonstration of in-mold assembly to create mesoscale revolute joint
  – No significant change in mold tooling costs because of in-mold assembly process
  – Cycle times for the process is comparable with macroscale in-mold assembly process
• We have developed mold design solutions which enable constraining premolded components to inhibit deformations
  – Characterization of forces on premolded component due to flow of molten polymer around it
  – Characterization of plastic deformation of premolded component due to flow of the molten polymer around it
Application in Minimally Invasive Neurosurgical Intracranial Robot (MINIR)

- Robot inserted through a surgical corridor carefully dissected by the neurosurgeon
- Tumor resection by liquefying tissue and washing out the debris
- Under direct control of human
- Targeting information obtained exclusively from frequently-updated MRI
  - Fully MRI-compatible device
- 0.3” – 0.5” diameter
Benefits

- Mesoscale In-mold assembly strategies used to manufacture prototype robot

- Radial support length of 1.27 mm used for in-mold assembly of each module

- SMA wiring capability illustrated by placeholder 24 gage wires

Weight 1.9 Grams

Two Different Orientations of In-Mold Assembled Robot Structure
Realizing Metal-Polymer Mesoscale Revolute Joints Using Insert Molding
In-mold Assembly using Insert Molding

**Advantages**
- Single shot molding utilized for in-mold assembly
- Joint made of rigid material (metallic insert) improves overall part quality
  - Pins do not deform due to polymer flow

**Issues**
- Optimization of joint size to ensure manufacturability
- Joint jamming has to be controlled
Controlling Joint Parameters

- Smallest possible joint dimensions should be used to minimize joint size
- Control joint friction due to radial stress $\sigma_{rr}$
- Prevent failure at weld-line

Where $\sigma_y$ is the yield stress and $FS_{WL}$ is the ratio of the weld line strength to base material

$$
\frac{\sigma_y}{FS_{WL}} = \sigma_\theta (r_p = r) = \frac{E_h \alpha_h \Delta T ((1+k)^2 + 1)}{(\nu_h + 1)((1+k)^2 - 1) + 2}
$$

Main contributor to $\sigma_{rr}$

Scaling parameter $k = (R-r)/r$

$$
\sigma_{rr} = \frac{E_h \alpha_h \Delta T h}{\nu_h + \frac{R^2 + r^2}{R^2 - r^2}} = \frac{E_h \alpha_h \Delta T}{\nu_h + 1 + \frac{2}{(k+1)^2 - 1}}
$$
Experimental Verification

- In-mold assembled joints manufactured using ABS polymer and brass inserts

Joint successfully fabricated at mesoscale (joint radius = 0.4 mm)

Joint jammed at Macroscale (joint radius = 3.175 mm)

Hoop stress v/s thickness ratio

Joint torque increase with joint sizes

Alternate method required for using in-mold assembly method at macroscale
Reducing Joint Interference Stress

• Step 1: Soft polymer molded on metallic insert
  – Initial radial interference stress $\sigma_{rr}'$ given by
    $$\sigma_{rr}' = \frac{E_s \alpha_s \Delta T_s}{(1 - \alpha_s \Delta T_s)(\nu_s + (r'^2 + r'^2)/(r'^2 - r^2))}$$
  – Outer radius ($r_{Pa}'$) of the shim
    • Decreases due to shrinkage
    • Increases due to interference in the inner radius
    $$r_{Pa}' = r'(1 - \alpha_s \Delta T_s) + \frac{r' \sigma_{rr}' r'^2 + r^2}{E_s \frac{r'^2 + r^2}{r'^2 - r^2}}$$

• Step 2: Base material molded on top of soft polymer
  – Principal of superposition used to calculate interference stresses
  – Final interference stress given by $\sigma_{rr}$
  – Final stress at the interface between shim and base material given by $\sigma_{int}$

Where:
$$\sigma = A^{-1} \delta$$
$$A = \begin{bmatrix}
    -\frac{r'}{E_s} & \frac{2r^2}{r'^2 - r^2} & \frac{r'}{E_s} \left( \nu_s + \frac{r^2 + r'^2}{r'^2 - r^2} \right) + \frac{r'}{E_h} \left( \nu_h + \frac{R^2 + r'^2}{R^2 - r'^2} \right) \\
    \frac{r}{E_s} \left( \nu_s + \frac{r^2 + r'^2}{r'^2 - r^2} \right) & \frac{r'}{E_s} & \frac{2r^2}{E_s} \left( \frac{2r}{r'^2 - r^2} \right) \\
    \frac{r'}{E_s} & \frac{2r^2}{E_s} & \frac{r'}{E_h} \left( \nu_h + \frac{R^2 + r'^2}{R^2 - r'^2} \right)
\end{bmatrix}$$
$$\sigma = \begin{bmatrix} \sigma_{rr} \\ \sigma_{int} \end{bmatrix} \quad \delta = \begin{bmatrix} r_{Pa}' \alpha_h \Delta T_h \\ r' \alpha_s \Delta T_s \end{bmatrix}$$
Macroscale In-mold Assembly: Results

- Analytical results show good agreement with finite element simulations to predict interface stresses.

- Analytical formulation can therefore be used to predict joint stresses and thereby select joint parameters for manufacturing in-mold assembled macroscale revolute joints using insert molding method.

![Graph showing interface stress for different thickness ratios (k)](image)

Successful macroscale joint manufactured by combining insert molding and multi-material molding.
In-mold Assembly of MINIR using Insert Molding

Step 1: Mold Assembly consisting of Metal inserts
Step 2: Single Shot Injection
Step 3 (a): Removal of Side Cores
Step 3 (b): Removal of Side Cores
Step 4: Ejection

Two different orientations of Neurosurgical Robot Structure

Summary

• Designed and developed in-mold assembly strategies using insert molding
• Developed analytical formulations for determining joint interface stresses in in-mold assembled revolute joints
• Designed and developed a mold design for manufacturing a 9 degree of freedom articulating structure for use as a robot
Embedding Shape Memory Alloy Actuators in Articulated Structures Using In Mold Assembly
Goals

• Design and develop molds for manufacturing an articulated miniature robot as an in-mold assembly using insert molding with embedded SMA

• Testing of SMA movement and force generation after the manufacturing process of the surgical robot
Molded articulated miniature robot with embedded actuators
Actuated articulated miniature robot after in-mold assembly

- Successful actuation of each joint of the robot in both directions
- Generation of sufficient force to smoothly actuate the joint

Realizing Multi-Material Miniature Mechanisms Using In-Mold Assembly
Challenges

• Hinge has to provide the desired range of motion
• Structure has to transfer loads
• Materials need to be connected
• Hinge has to be accurately positioned for in-mold assembly
• Miniature scale of the mechanism can impose additional space constraints

Link fracture examples

Hinge fracture examples

Anchoring feature plastic deformation
Anchoring feature shearing
Hinge displacement due to lack of positioning features
Identification of Hinge Geometry

- Necessary hinge geometries
  - Flexing section
    - Enable rotation
    - Transfer load
    - Flash prevention
    - Fatigue resistance
  - Positioning feature
    - Positioning inside 2nd stage mold
  - Interlocking features
    - Hinge anchoring in the link
    - Load transfer
- Encapsulating link volume

![Diagram of hinge geometry](image-url)
Identification of Hinge Geometry (Cont.)

- Parametric model for optimization
  - Number of parameters: 15
  - Number of constraints: 7

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<td>Breadth (along rot. axis)</td>
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Overall Approach

Elaborate Mechanism Shape

Mechanism Concept

Design Requirements

Manufacturability Rules

Interconnection of Miniature Hinges

Determine Joint Geometry

Mechanism Parametric Model

Hinge Parametric Model
Parametric Optimization
Mechanism Design Level

- **Mechanism Design Analysis:**
  - Kinematic analysis (ADAMS)
  - Finite element analysis (ProMechanica)

- **Results:**

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Parametric Optimization
Hinge Design Level

- Optimization approach:

- Results:

**LDPE**

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**HIPP**

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Example of Optimized Assembly

• Hinge design optimized for MAV drive mechanism
  – Transferring torque from high-power brushless motor to the wings
  – High-impact polypropylene as hinge material

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Gate and Runner Design

• Goals
  – Ensure mold filling
  – Provide for required flow patterns

• First stage molding (hinge)
  – Film gate aligned with hinge rotation axis
  – Sacrificial features supporting demolding

• Second stage molding (mechanism)
  – Gate location constrained with respect to the properties of second stage filled polymer moldings (fiber alignment)
  – Multi-link compliant mechanism in-mold assembly results in multi-cavity molds with complex runner system

Creating Flapping Wing Micro Air Vehicles

• Attributes of fixed wing flight
  – High forward speeds required for generating lift
  – Low maneuverability
  – Difficult to operate in confined spaces

• Attributes of rotary wing flight
  – Low forward speeds and hovering possible
  – High frequency leads to noisy operation

• Attributes of flapping wing flight
  – Low frequency flapping leads to quiet flight
  – Low forward speeds lead to high maneuverability
  – Ability to use in surveillance operations
Results

- Successful in-mold assembly of multi-material compliant MAV drive frame
- MAV tested to be capable of:
  - Remote launch from a four-wheel RC vehicle
  - Sustained outdoor flight with controlled ascent, descent, and steering
  - Controlled landing in a safe area
  - High degree of realism (falcon attacks)

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*with 21.1g 3x250mAh-cell li-po battery pack


http://www.youtube.com/watch?v=qJmeFKf0l-g
Summary

- Established technical feasibility for creating multi-material compliant structures with miniature hinges using injection molding process
- Developed design optimization approach for creating multi-material compliant mechanisms using multi-material molding
- Implementation on a successfully flying MAV
Embedding Actuators in Thermally Conducting Polymers Using In-Mold Assembly
Motivation

- Low heat dissipation from actuators embedded in structures of traditional unfilled polymers
  - Excessive heat can overheat and damage the structure
- Can emerging thermally conductive polymer composites help to overcome this issue?
Thermally Conductive Polymer Composites

- Easily injection-molded
- Thermal conductivities an order of magnitude higher than bulk polymers
- Adding function to part structure – heat dissipation
- Thermal and mechanical characteristics depend on filler orientation

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<td>Flexural Strength</td>
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<td>59</td>
<td>109</td>
<td>ASTM D790</td>
</tr>
<tr>
<td>Melt Temperature Range</td>
<td>°C</td>
<td>190 to 270</td>
<td>260 to 277</td>
<td></td>
</tr>
</tbody>
</table>
Using In-Mold Assembly for Embedding DC Motor

- In-mold assembly of a simple gearbox-like structure:
  - Didel “Blue SS” 7mm DC pager motor (max 1.5 W)
  - brass sleeve for output shaft
- Pager motor produces heat
  - will overheat and fail when embedded in regular bulk polymer
- In-mold assembly challenge:
  - Preliminary experiments showed excessive motor housing deformation due to polymer pressure during injection molding
Embedding DC Motor Process Optimization

- Determination of injection pressure:
  - Ansys model of the motor housing
  - FEA to obtain allowable injection pressure
Embedding DC Motor Temperature Measurement

- In-mold assembled samples:

- Motor temperature measurement:
  - Constant load applied to motor shaft
  - Power generation (1.5W) controlled by voltage and current

- Results:
  - Unfilled Nylon12 (Grilamid L16): 96.0°C
  - Filled Nylon12 (NJ-6000 TC): 65.5°C

Motor embedded in unfilled polymer runs 46% hotter!

Summary

• Thermally conducting polymers show significantly improved thermal performance compared to unfilled polymers
• Demonstrated applicability of thermally conductive polymers towards creating multi-functional structures with embedded actuators using in-mold assembly
Conclusions

- In-mold assembly enables large design space
  - Bio-compatible polymers
  - Parts with small features
- In-mold assembly enables realization of joints to transfer power and motion
  - Revolute, Prismatic, Spherical
- In-mold assembly enables embedding of prefabricated components in the structure without damaging them
  - Actuators, Batteries, Sensors

In-mold assembly brings together many exciting developments in manufacturing
Future Directions

• In-situ in-mold assembly for repair and on-the-site structure modifications
• Integrating energy harvesting technologies in molds
• Modular robotics components for cavity morphing
• Continuous cavity morphing
• Further Miniaturization
• Managing anisotropy in composites
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