Overview of Multi-Piece Mold Design Research at the Advanced Manufacturing Lab

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1 Introduction

Conventional molds, usually referred to as two-piece molds have only one primary parting surface and consist of two major pieces: *core* and *cavity*. These two pieces are separated along a single parting direction to eject the molded part. Since the mold pieces are constrained to move in a single direction, several undercuts are encountered in case of complex industrial parts. A number of side cores are required to form these undercuts. The side cores, apart from being very costly complicate and slow down the molding operation. Some very complex parts may not even be producible using a two-piece mold.

Multi-piece molds overcome the restrictions imposed by traditional molds by having many parting directions. These molds have more than one primary parting surface and consist of more than two mold pieces or subassemblies. Each of these mold pieces has a different parting direction. This freedom to remove the mold pieces from many different directions eliminates the undercuts produced by two-piece molds. A multi-piece mold can be visualized as a 3D jigsaw puzzle, where all the mold pieces fit together to form a cavity and then can be disassembled to eject the molded part. Moreover, since there are no actuated side cores in multi-piece molds, the tooling cost is significantly low. This makes multi-piece molding technology an ideal candidate for making geometrically complex ceramic objects. The ability to manufacture geometrically complex objects economically will significantly expand the design space and will allow development of new products in many different areas.

Currently, multi-piece molds are not widely used because of lack of knowledge and required expertise to design these molds. The complete automation of mold design will radically reduce the cost and lead-time associated with the deployment of multi-piece molds and hence make them a viable candidate. Therefore, in this project we have focused on automated design and fabrication of multi-piece molds.

Our lab has developed several mold design tools to automatically design multi-piece molds. This report presents a summary of our research accomplishments.

2 Feature-Based Approach for Designing Multi-Piece Sacrificial Molds

Gelcasting is emerging as a popular method for making high performance ceramic parts for a wide variety of aerospace, automotive, and industrial applications. Low pouring temperatures in gelcasting enable use of both sacrificial as well as permanent molds. Ceramic parts cannot be easily assembled together. Therefore, it is important to make them as a single component. This often requires them to be highly complex in shape. Multi-piece sacrificial molds are an attractive option for realizing geometrically complex ceramic parts.

We have developed a feature-based algorithm for automated design of multi-piece sacrificial molds. For those class of parts that can be modeled using our feature-based representation, the feature-based decomposition and concave edge-based decomposition steps ensure accessibility of mold components and therefore circumvent the need for explicit global accessibility computations.

The main benefits of our algorithm are enumerated below.

1) Our algorithm tends to create mold partitions in which parting planes contain natural edges of the object. In case of ceramic parts, such partitioning is preferred over partitioning in which the parting plane passes through the middle of a face of the object due to reduction in need for secondary operations.

2) This approach allows us to manufacture parts that could not be produced earlier using two-piece molds. Thus it expands the design space for parts that can be produced using casting processes such as gelcasting and polyurethane manufacturing.

3) Since this approach automatically produces solid models of mold components, it can be integrated with CAM systems to generate the cutter path plans for manufacturing the individual mold components. Thus an integrated system can be developed that can simultaneously design and generate the cutter path plans for manufacturing the individual mold components in a mold assembly.

3 Accessibility-Based Spatial Partitioning to Generate Multi-Piece Sacrificial Molds

We have developed a new algorithm for determining the set of directions from which a triangular facet is inaccessible due to another triangular facet. This algorithm corresponds to the exact mathematical definition of semi-infinite inaccessibility region and is easy to implement. We carried out detailed computational experiments with twenty different objects of varying complexity. Accessibility analysis results for all objects were computed in less than two minutes. We believe that the running time will be approximately one third to one fourth of the time reported on a high-end workstation. This approach presents an improvement over previous approaches in the following aspects:

- A provably sound algorithm has been developed for computing the exact inaccessibility region for a facet due to the presence of another facet.

- Based on the above algorithm, both exact and approximate approaches have been developed to compute the accessibility cones for polyhedral objects. The approximate approach is conservative in nature - it makes errors on the safer side and is guaranteed to correctly identify all inaccessible facets on the boundary of the object.

We have developed an algorithm based on accessibility-driven partitioning approach to automate the design of sacrificial multi-piece molds. The algorithm presented in this report analyzes the accessibility of the gross mold shape and partitions it using accessibility information. Each partitioning step improves accessibility of decomposed mold pieces. By performing successive decomposition, this algorithm finally produces a set of mold components that are accessible and therefore can be manufactured using milling and drilling operations. We have developed a hybrid approach to finding feasible partitioning planes for solving the accessibility problems on the gross mold shape. We first generate and evaluate a set of a finite number of partitioning planes using enumerative method. Then we improve the quality of the set by locating addition feasible partitioning planes in the vicinity of near-miss planes in the set through analytical method.

Finally we determine the near-optimal set of partitioning planes using set-covering techniques. We have tested this approach on the automated mold design for several geometrically complex parts. 1 to 3-cut solutions were generated for the molds of these parts. Our accessibility-based decomposition presents an improvement over previous approaches in the following aspects:

- It uses global accessibility information and therefore can find solutions that cannot be found by using local information such as undercuts and curvature. The spatial partitioning approach is capable of locating partitioning planes using analytical formulations in the vicinity of promising regions and therefore it can construct more complete search space compared to previous approaches that use heuristic techniques.

- It uses hybrid problem solving strategy. It first tries to find an optimal solution. If an optimal solution with the user-specified characteristics does not exist, then it uses state-space search to find the best possible solution in the given amount of computation time.

4 Automated Generation of Multi-Piece Permanent Molds

We have developed a multi-piece permanent mold design algorithm to automate several important mold-design steps: finding parting directions, locating parting lines, creating parting surfaces, and constructing mold pieces. This algorithm constructs mold pieces based on global accessibility analysis results of the part and therefore guarantees the disassembly of the mold pieces. We have also developed a software system, which has been successfully tested on several complex industrial parts.

Our approach is a significant improvement over the previous approaches with respect to the following characteristics:

1) *Domain*: The previous mold splitting algorithms were either limited to two-piece molds or planar parting surfaces. A disassembly-based algorithm was developed that guarantees the disassembly of the mold assembly. The algorithm can create parting surfaces for non-planar parting lines also.

2) *Soundness*: The previous algorithms found parting directions using a local approach. Our algorithm locates the parting direction of a face is in the global accessibility cone of the face. Global accessibility is important because it ensures that the mold can be disassembled. This fact also enables the design of multi-piece multi-cavity molds. Also, in contrast to the Z-buffer approach that gives approximate solution in the image space, our algorithm determines exact accessibility in the object space. It is also capable of robustly handling near-vertical faces by compensating for the surface tolerance of the part.

3) *Completeness*: In contrast to approaches that sample parting directions, our algorithm performs global accessibility analysis of the part to find the candidate parting directions. This ensures that the candidate parting direction set is complete.

4) *Efficiency*: For efficient implementation of the algorithm, conditions based on polyhedral part properties were developed to prune unnecessary obstruction tests. Our algorithm successfully designed valid multi-piece molds for representative parts from industry within 5 minutes.

5) *Solution Quality*: A hybrid approach combining breadth-first and depth-first search was developed to find a near-optimal solution within a user-specified time limit. Our algorithm, within a reasonable time, always returns an optimal solution when the numbers of sets in the solution is small (2-4). On more complex parts it is capable of finding feasible solution. However, optimality cannot be guaranteed in such cases.

Limited volume production is increasingly becoming a common industrial practice in the era of mass customization. Prototyping is also almost always done to eliminate errors in a design before finalizing it. Since molds are constantly changed in prototyping and limited volume production, it is required that the tooling cost is low. Since multi-piece molds can be produced cheaply, this technology is an ideal candidate for limited volume production and prototyping. By making polyurethane prototypes using urethane molds, the costs can be further brought down. Some solid freeform fabrication technologies would cost approximately ten times the cost of urethane-molded parts. Multi-molds are also capable of producing very complex parts. Some parts that cannot be produced by traditional molds can easily be produced by multi-piece molds.

5 Automated Design of Side Cores

We have developed algorithms for generating shapes of side actions to minimize a customizable injection molding cost function. Given a set of undercut facets on a polyhedral part and the main mold opening directions, our approach works in the following manner. First, we compute candidate retraction space for every undercut facet. This space represents the set of candidate translation vectors that can be used by the side action to completely disengage from the undercut facet. As the next step, we generate a discrete set of feasible, non-dominated retractions. Then we group the undercut facets into undercut regions by performing state space search over such retractions. This search step is performed by minimizing the given molding cost function. After identifying the undercut regions, we generate the shapes of individual side actions.

The major contributions of our algorithm can be summarized as follows.

- It is capable of designing side actions for complex undercuts that are finitely accessible. Previous approaches were primarily applicable for external undercuts which exhibit semi-infinite accessibility.

- It correctly reports that certain undercut regions may not have any feasible side actions unlike some of the existing techniques that require some kind of post-processing operations to arrive at similar conclusions. Hence, significant re-designing can be easily carried out at an early enough stage for such parts that are non-moldable in their present forms. This is also useful in determining infeasible molding sequences in multi material injection molding.

- It partitions connected undercut regions (for which no single side action exists) into smaller regions, such that each of them can be molded by separate side actions and a customizable molding cost function is minimized. To the best of our knowledge, no prior work has focused on this particular aspect of side action design problem.

- Many of the steps in the computation of candidate retraction space and discrete set of feasible retractions have linear or linear-logarithmic worst-case asymptotic time complexities. Few grow quadratically with an increase in the total number of part facets as well the number of undercut facets.

- If a connected undercut region can be molded by 3 or fewer number of side actions, then our empirical results suggest that our algorithm is capable of finding a solution very close to the optimum solution in a reasonable amount of time for most practical parts.

6 One Click Mold Design Tool

We have developed one-click mold design software for rapid tooling application. Our software designs the mold for a given object with a single mouse click and hence it significantly reduces mold design time. Currently it is only limited to parts that can be made using a two-piece mold. It has been written in C++ and runs on Microsoft Windows. Following are the specifications of the software:

Input file format: Stereolithography files (STL)

Output file format: STL files

The software has two modes: automatic and interactive. The automatic mode performs all the above steps with a single mouse click. The interactive mode allows the designers to create the mold geometry manually or to modify the design produced by automatic mode. Figure 1-5 shows the snapshots of the software in action. We have tested the software on more than 50 test parts from industry. Figure 6 and 7 show representative test parts. We have observed that the automatic mode produces optimal designs on most of the parts. Modifications to the designs produced by the automatic mode are needed in very few cases.

We have developed an extremely efficient accessibility analysis algorithm that takes surface tolerance into account. We accelerate the accessibility calculations by using spatial hierarchical data structures. It takes only 2 seconds to process 5000 facets. The surface tolerance issues are addressed by perturbing the facet coordinates.

We partition the part boundary into three regions – *CORE*, *CAVITY*, and *BOTH*. BOTH region is a belt of facets between core and cavity that can be assigned to any of them. This belt provides a feasible region E. We have developed a new algorithm to find the flattest possible parting line even on non-convex polyhedron. A loop of parting edges $l = \{e_1, e_2, \ldots, e_k\}$ is chosen in E for which the flatness criterion ρ is maximum. ρ is defined in the following manner:

$$\rho = \frac{\sum_{i=1}^{k} length(\hat{e}_i)^2}{\sum_{i=1}^{k} length(e_i)^2}$$

Where $\hat{e}_i$ is the projection of e_i on a plane perpendicular to the parting direction of the mold-piece region. It can be seen that $\rho \leq 1$. It is equal to one only if the parting loop is planar.

A *Parting Surface* is the contact surface of the two mold pieces. It is used to split the gross mold into different mold pieces. A mold-piece region has one outer parting loop and may have multiple inner parting loops. A parting surface is required for each parting loop. Different methods are used to create parting surfaces for the outer loop and the inner loops. Union of all the parting surfaces gives one parting surface with disconnected patches.

The outer parting surface is created by sweeping the edges of the outer parting loop. We have developed a new algorithm to find the best sweep direction. Parting surface for an inner loop is created by covering the loop by a triangulated surface. Covering is a surfacing method to fit a surface over the boundary defined with a closed and connected circuit of curves.

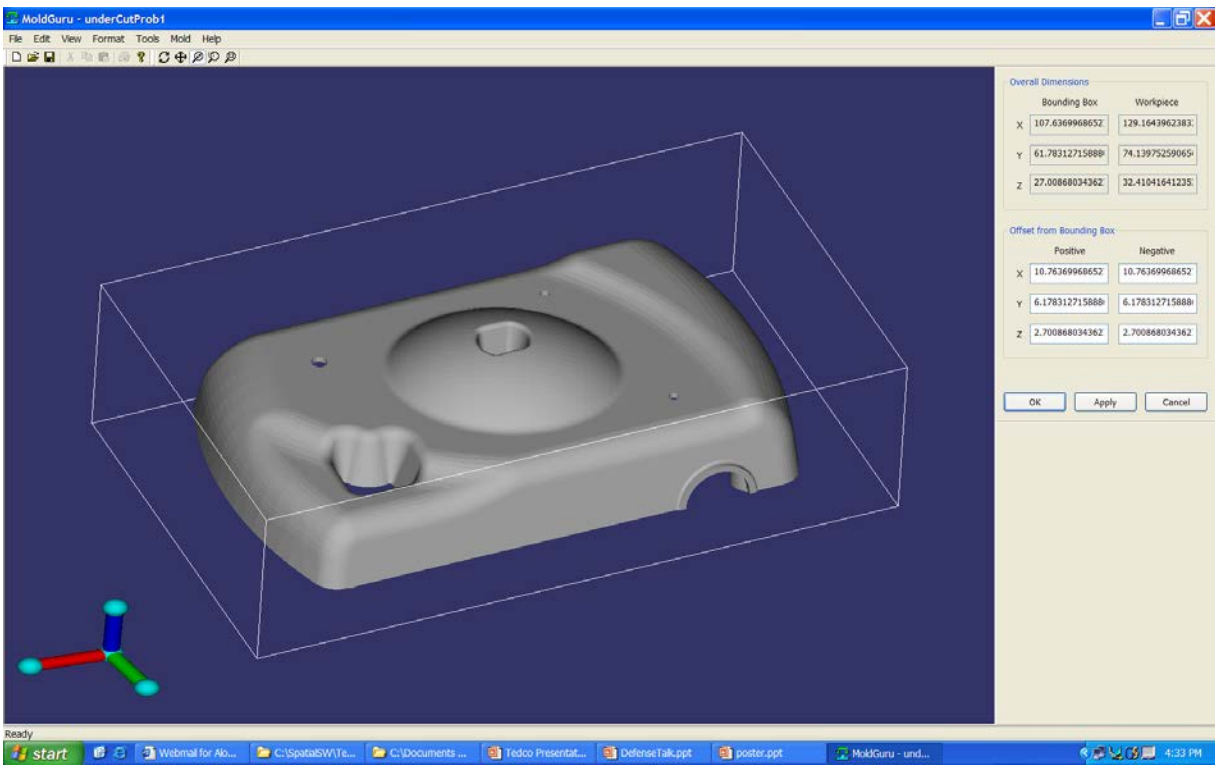

Figure 1: Create Workpiece

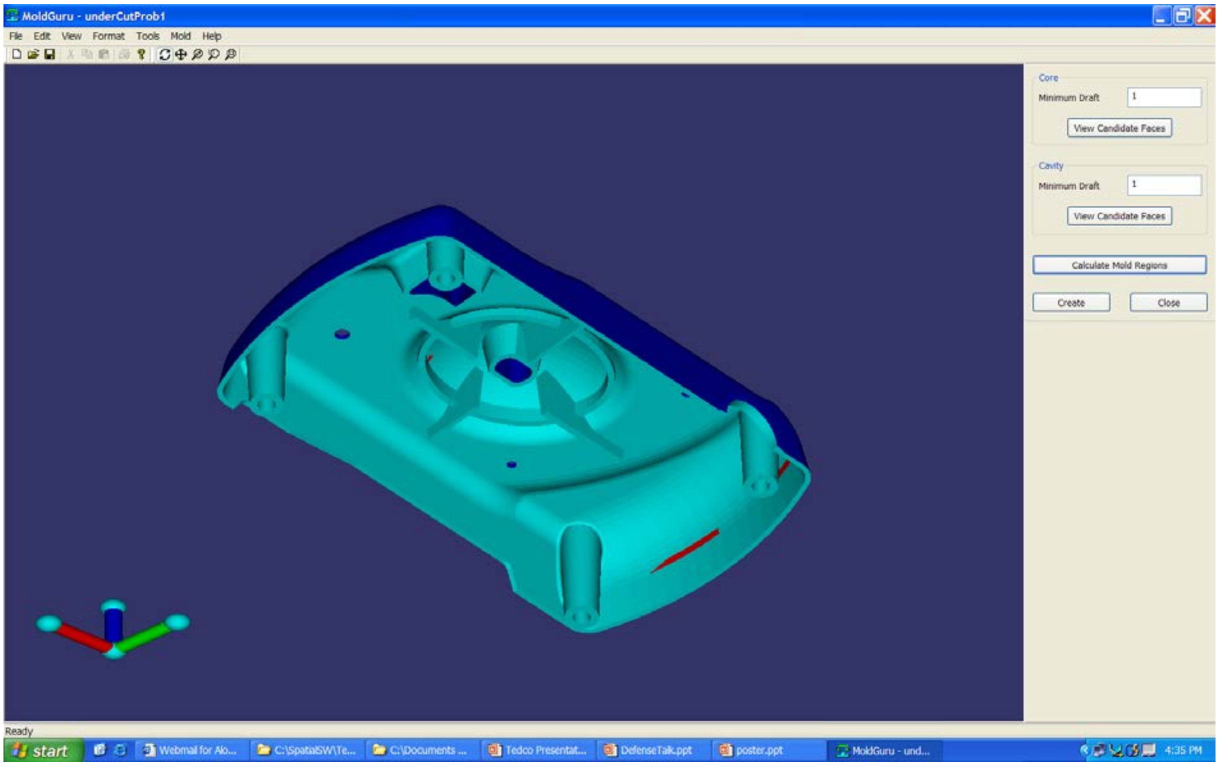

Figure 2: Detect Undercuts

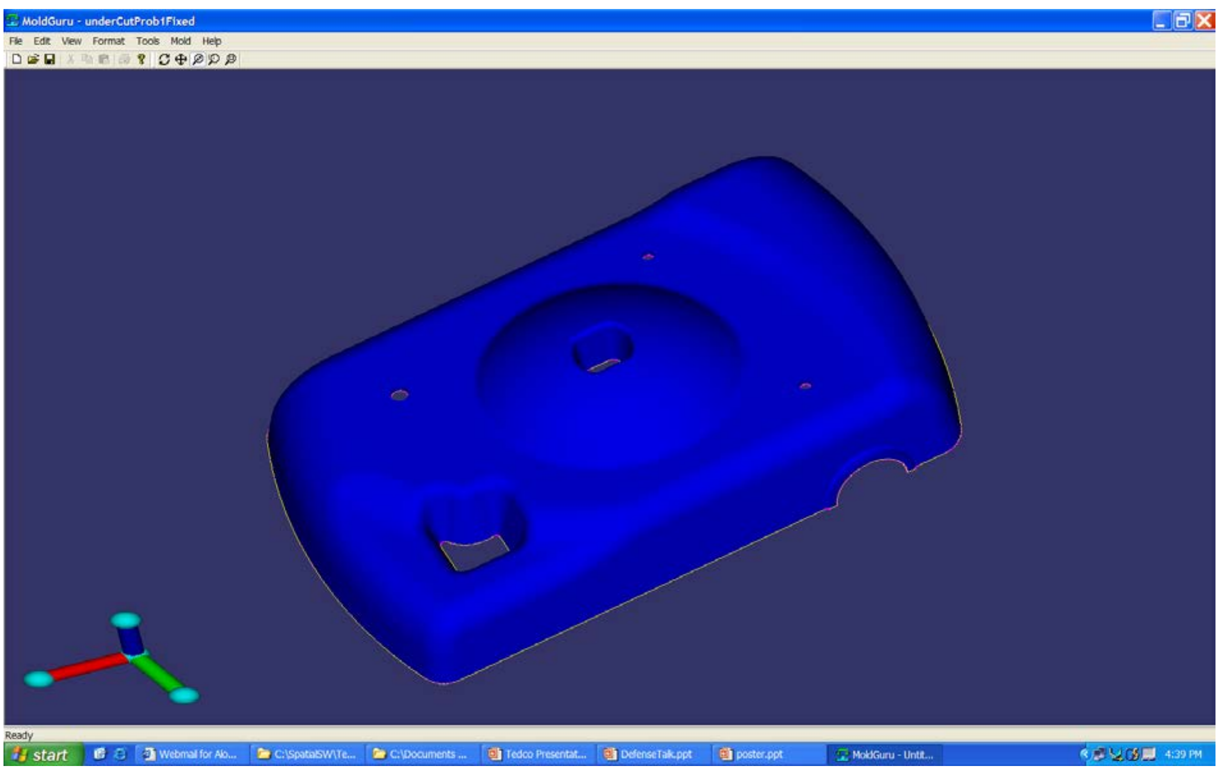

Figure 3: Create Parting Line

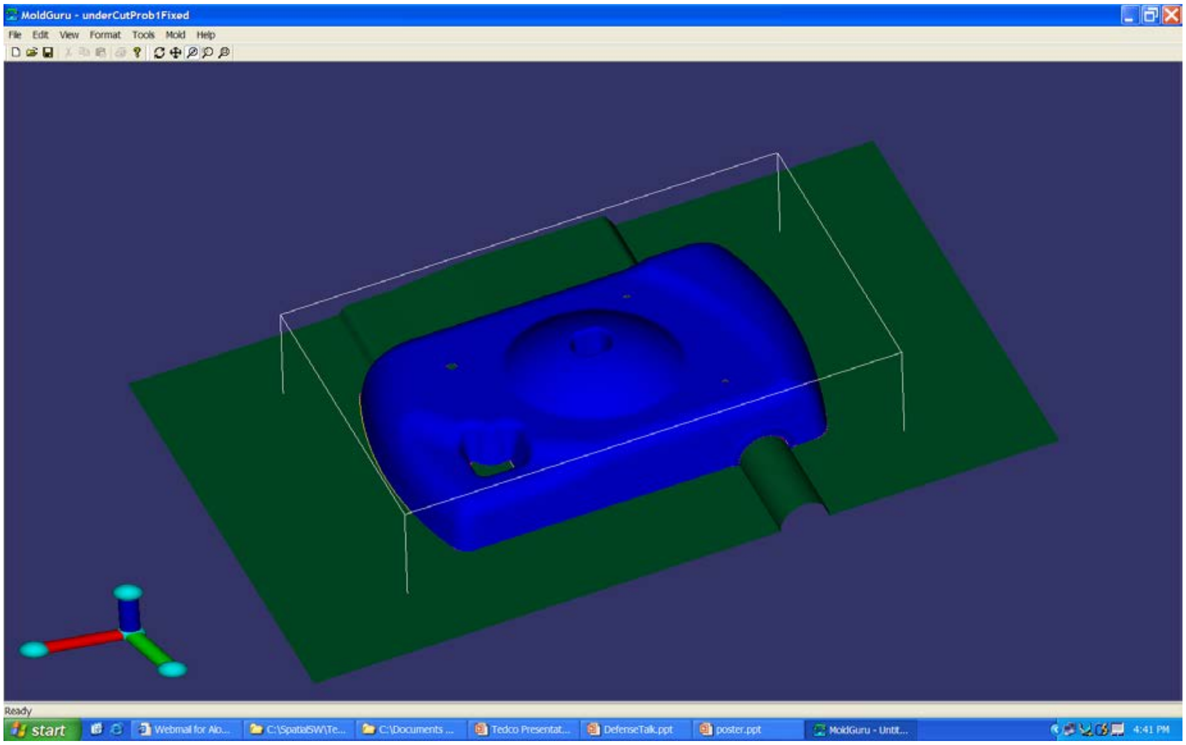

Figure 4: Create Parting Surface

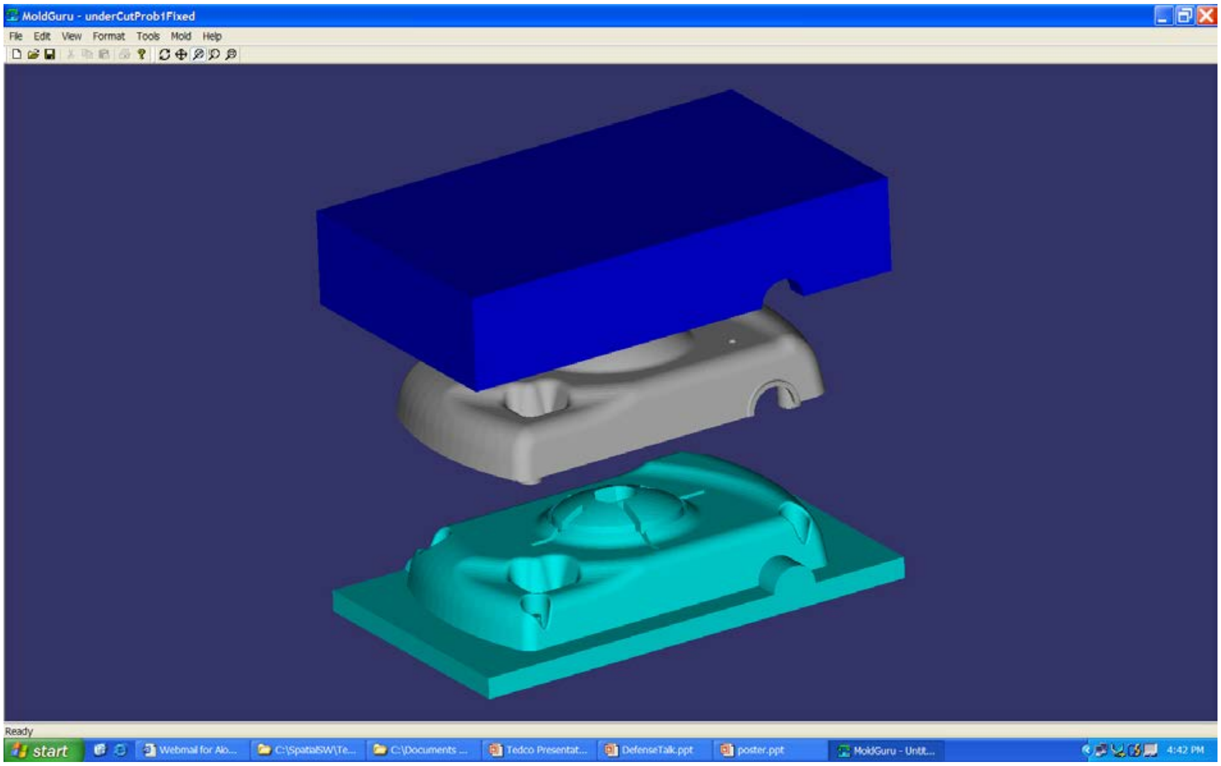

Figure 5: Split Workpiece

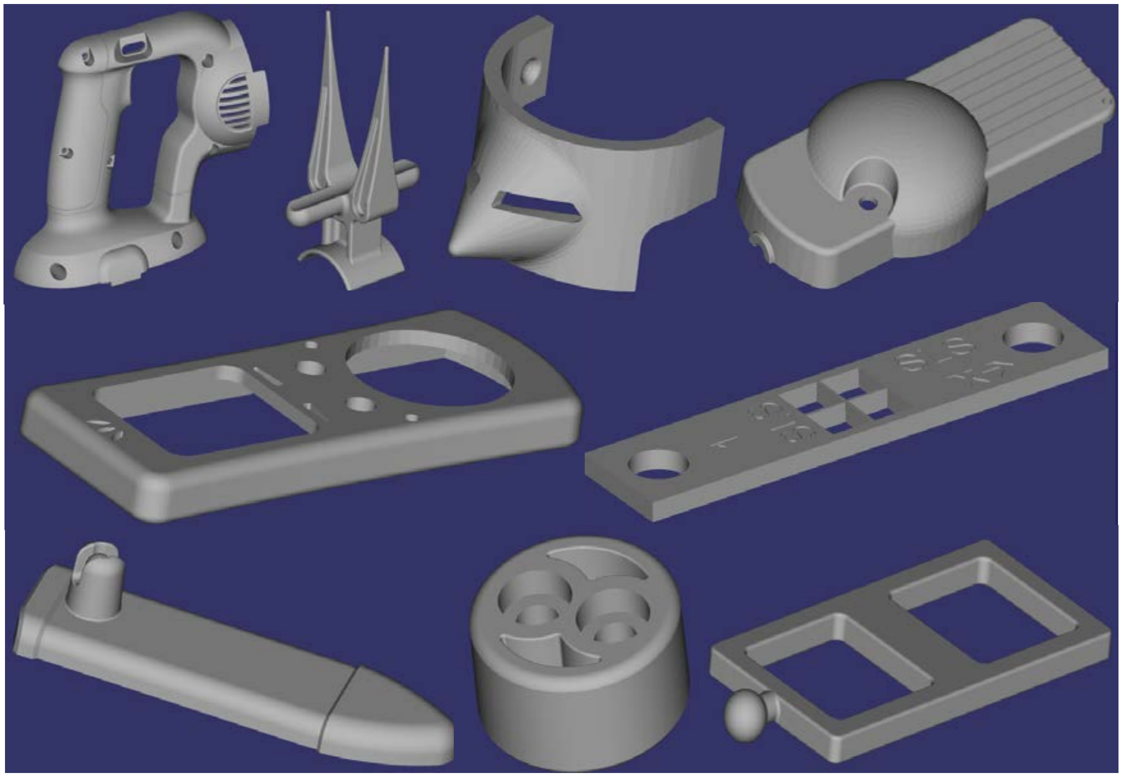

Figure 6: Example Parts on Which Our Algorithm Works

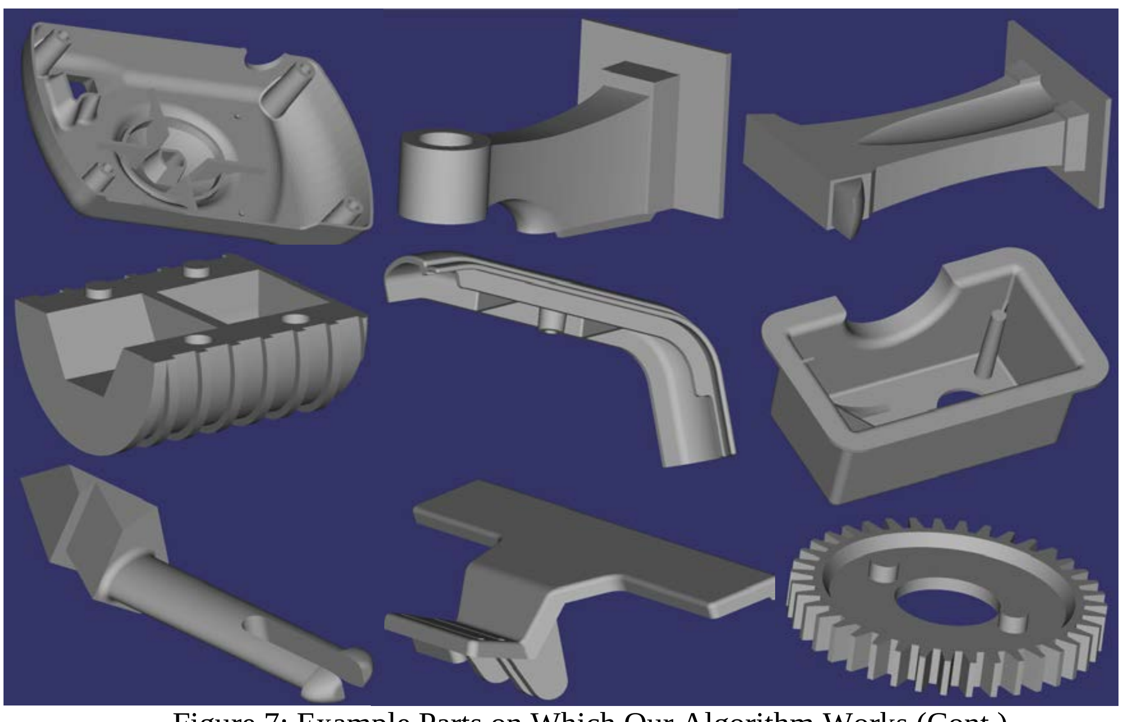

Figure 7: Example Parts on Which Our Algorithm Works (Cont.)

7 Conclusions

Anticipated benefits of the One Click Mold Design tool described in this report are as following:

- Fully automated mold design software significantly reduces the mold design time, and converts largely human tasks to automated, computerized functions. This reduction in mold design time should translate to cost savings and reduction in time-to-market while ensuring optimal mold design and high product quality.

- Many users of injection molding processes operate in highly cyclic industries in which quality is a key differentiator. A software tool that brings reduction in time-to-market while maintaining high quality should be quite beneficial to such users to fully exploit their available market windows.

- Fully automated mold design software also enables highly automated cost estimation and hence significantly reduces the time and effort needed to develop accurate cost estimates. This will help mold designers to quote more jobs, resulting in increased revenues.

- Many plastic part designers often need to consult with mold designers to understand the implications of various part features on mold complexity – an area that falls outside the expertise of most plastic part designers. These interactions often lead to long part and product development times, and often limit the number of alternatives that a part designer can consider, sometimes leading to sub-optimal designs. Fully automated mold design software ensures that mold design expertise will be only one click away from part designers. Therefore, part designers should be able to understand the implications of various design possibilities, and hence create optimal designs that deliver the desired functionality with the least manufacturing cost.

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