User-Guided Grasp Planning for Digital Hand

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Abstract

In order to assemble a part (of e.g., an engine), a human hand must obtain complete control of its motion through application of forces and toques at multiple contact points. Today, it is often time-consuming to synthesize a good hand grasp of a part using Digital Human Modeling (DHM) tools because these tools require detailed manual inputs from a user such as manually placing a digital hand around a feasible grasp location and then closing the fingers around the part. In a previous paper, we presented two different methods (i.e., Pointwise Shortest Distance and Environment Clearance) to color part surfaces by taking environmental distance constraints into account so that a user such as an assembly simulation expert can easily identify feasible grasp locations. Due to the robustness of the implementation, even triangle meshes with common geometric flaws such as cracks and gaps can be handled. In this paper, we leverage on this feasibility analysis and present a user-guided grasp planning approach that significantly speeds up the grasp modeling process. First, the user selects a predefined grip type and then sets an approach direction for the hand. To synthesize many grasps, we randomly sample the hand's rotation around the approach direction. Next, the hand is moved towards the part until the hand's Grasp Center Point (GCP) reaches the geometry of the part or a collision between the hand and the part is detected. If a collision was detected, we move the hand backwards until there is no collision between the hand and the part anymore. Finally, we close the hand's fingers around the part to synthesize a grasp. In this way, we can quickly synthesize a multitude of grasps and let the user choose among the ones with the best grasp qualities, where each grasp quality is computed using the corresponding 6D grasp wrench hull. We believe that this user-guided grasp planning approach can significantly enhance DHM tools such as Intelligently Moving Manikins (IMMA) when it comes to user usability.

Keywords: Assembly Simulation, Digital Human Model, Ergonomics, Grasping, Visualization.

Introduction

Before fabricating a physical prototype, a DHM tool such as IMMA (Högberg, Hanson, Bohlin, & Carlson, 2016) in the Industrial Path Solutions (IPS) platform can be used to evaluate both human-product interactions and human-production system interactions. To assemble a part such as the Central Electronic Module (CEM) box shown in Figure 1, a feasible grasp location for a manikin must be identified prior to the grasping of the part by a manikin hand.

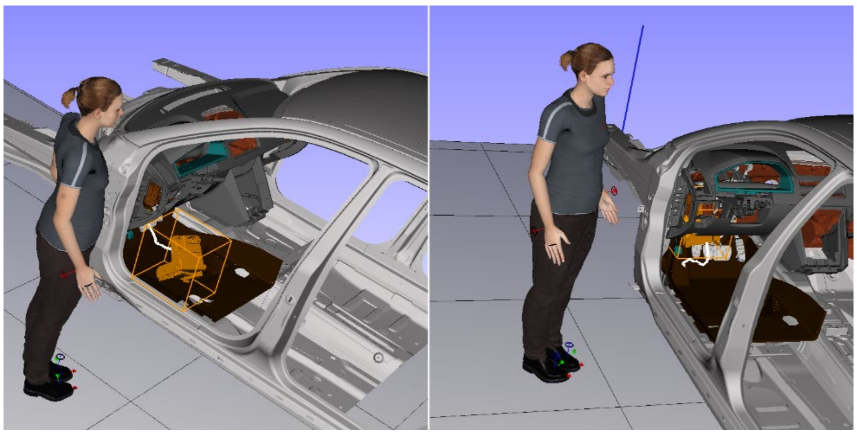


Figure 1. To assemble the Central Electronic Module (CEM) box, the manikin must grasp it and then move from its start pose (i.e., the combination of position and orientation) shown in the left subfigure to its goal pose shown in the right subfigure while following the path shown in white.

In the field of robotics, many researchers assume that the part to be grasped is alone (Li, Saut, Pettré, Sahbani, & Multon, 2015) (i.e., the grasp planner does not need to take into account any other objects) and the manipulator is disembodied (i.e., the kinematics of the robot is not taken into account). Consequently, most DHM tools still rely on teleoperation or hand scripted grasps. As the first step towards autonomous grasp planning in IPS IMMA, we presented two methods called *Pointwise Shortest Distance* and *Environment Clearance* in (Li, Kressin, Vajedi, & Carlson, 2017) to visualize part surfaces so that best collision-free grasp locations can be easily identified. Pointwise Shortest Distance is designed so that surfaces of a part can be colored as fast as possible (i.e., at a low computational cost), because the color at each vertex is simply determined by the shortest distance between it and the environment (i.e., the obstacle objects). On the contrary, Environment Clearance (Berenson, Diankov, Nishiwaki, Kagami, & Kuffner, 2017) is much more computationally expensive because it relies on the clearance along the normal vector at each vertex to handle parts with complex shapes. In (Li, Kressin, Vajedi, & Carlson, 2017) and in this paper, both the part to be assembled (or disassembled) and the environment are represented by triangle meshes. Since many triangle meshes are not always consistently oriented (i.e., the normal vectors sometimes point in the "wrong" directions), our GPU-based algorithm called *Visual Shell* is applied in (Li, Kressin, Vajedi, & Carlson, 2017) to flip inconsistently oriented normal vectors. The upside of Environment Clearance is that it is much better at isolating/highlighting potential grasp locations than Pointwise Shortest Distance. In Figure 2, both methods are applied to color the surfaces of the tunnel console, which is the part that has to be disassembled. As shown in the left subfigure, several surface patches on the left side of the tunnel console are colored in red using Pointwise Shortest Distance, because triangle vertices on these patches are located very close to either the gear stick or the handbrake, even though these patches can be easily accessed by a manikin hand. However, these surface patches are rendered in blue in the right subfigure where Environment Clearance is used instead.

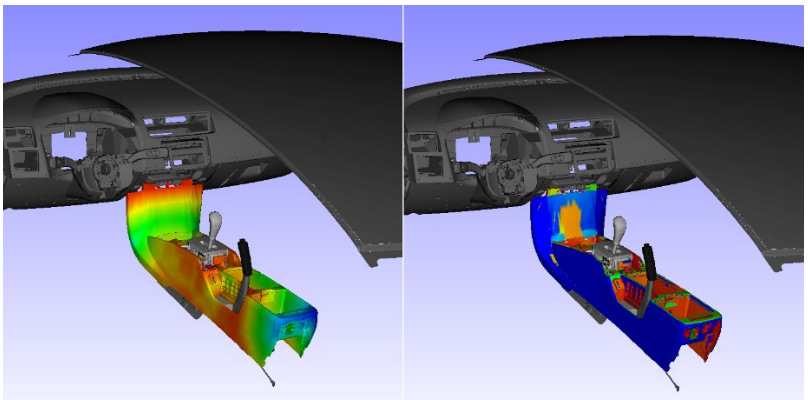


Figure 2. The tunnel console is colored using Pointwise Shortest Distance in the left subfigure, whereas Environment Clearance is used to color the surfaces of the tunnel console in the right subfigure.

After determining feasible grasp locations for a manikin in (Li, Kressin, Vajedi, & Carlson, 2017), an IMMA user still has to manually place the hand at a grasp location and then close the fingers to grasp the part. This procedure not only is time-consuming, but also does not evaluate newly synthesized grasp (i.e., computing the corresponding grasp quality). In this paper, the grasp modeling procedure is significantly easier because the user only needs to define a single approach direction that the hand has to follow during the synthesis process. In this way, many grasps can be quickly synthesized, and the user only needs to select one of these grasps that have *closure* (i.e., these grasps can be maintained for every possible disturbance load) at the end. There are two types of grasp closure: *form closure* and *force closure*. We are only concerned with force closure in this paper because a force closure grasp (also called a precision grasp) is able to balance any disturbance by applying forces with friction at contact points and hence requires fewer contact points than are required for a form closure grasp (also called power grasp or enveloping grasp).

Methods

In this section, we present a user-guided grasp planning approach that significantly speeds up the grasp modeling process after giving a short description about how we model and evaluate a grasp from a mathematical perspective.

IMMA Hand Modeling

The configuration of an IMMA hand is high-dimensional (with 19 bones, 19 joints, and 32 degrees of freedom (DOF)). It is modeled by Rectangular Swept Spheres (RSSs) (Larsen, Gottschalk, Lin, & Manocha, 2000) (see Figure 3) when contacts between the hand and the part are queried. Furthermore, IMMA comes with 9 predefined grip types (i.e., Chuck Grip, Closed Hand, Cylindrical Power Grip, Diagonal Power Grip, Lateral Pinch, Parallel Extension, Prismatic 4F Pinch, Spherical Grip, and Tip Pinch as shown in Figure 4). For each grip type, IMMA also defines the corresponding two sets of joint angles describing the open hand configuration and the closed hand configuration, respectively. A hand can be opened/closed by simply interpolating the joint angles between these two configurations as shown in Figure 3.

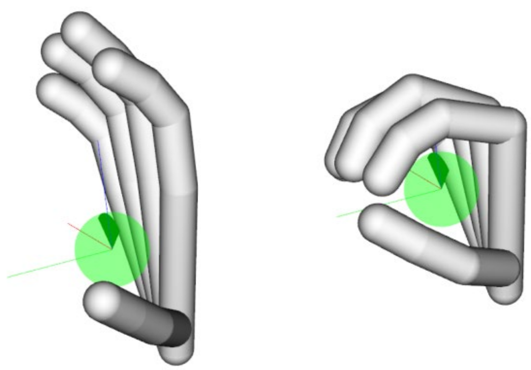


Figure 3. Spherical grip's open hand configuration and closed hand configuration, respectively.

Grasp Modeling and Grasp Evaluation

An IMMA manikin obtains complete control of the part's motion by grasping it through application of forces and torques at multiple contacts between the hand and the part. Because the configuration of a manikin hand is high-dimensional and the geometry of the part restricts the space of feasible contacts, it is a challenging task to synthesize a stable grasp. To simplify the task of grasping a part, point-on-plane contact models are used in this paper in grasp analysis because neither point-on-point contact nor point-on-line contact is stable. Additionally, possible contact points for most objects are seldom sharp edges or points.

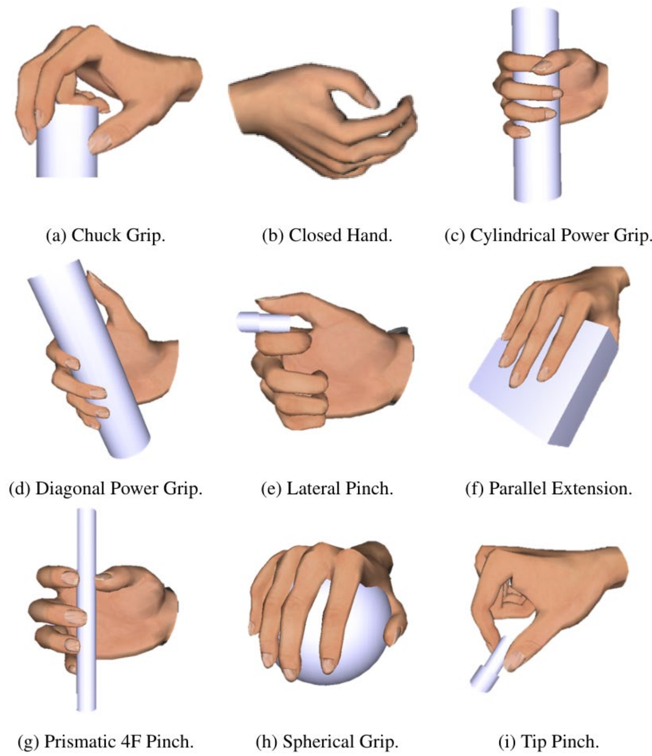


Figure 4. Predefined grip types in IMMA.

Assume that after the hand is closed around the part, there are k contact points. If we assume that these contact points are not frictionless, then the forces that don't lead to slipping (i.e., the admissible forces) can be defined by a *friction cone* (as shown in the left subfigure in Figure 5):

$$\mathcal{F} = \{\boldsymbol{f} \mid \|\boldsymbol{f}_{tangent}\| \leq \mu\|\boldsymbol{f}_{\perp}\|, \quad f_z \geq 0\},$$

where μ is the coefficient of static friction associated with the surface, $\boldsymbol{f} = \boldsymbol{f}_{\perp} + \boldsymbol{f}_{tangent}$ is the total force acting on the part at a contact point, $\boldsymbol{f}_{\perp} = [0, 0, f_z]$, $\boldsymbol{f}_{tangent} = [f_x, f_y, 0]$, and the positive z-direction points in the direction of the part's surface normal at the contact point and into the part. It is very convenient from a computational standpoint to *inner* approximate the true friction cone with a pyramid. In the right subfigure in Figure 5, the pyramidal inner-approximation of the friction cone is defined by 8 vectors (i.e., $\boldsymbol{f}_1, \cdots, \boldsymbol{f}_8$).

Given a grasp defined by k contact points and the corresponding k linearized friction cones $\mathcal{F}_i$ defined by m bounded forces $\{\boldsymbol{f}_{i,1}, \boldsymbol{f}_{i,2}, \cdots, \boldsymbol{f}_{i,m}\}$, the *grasp wrench space* $\mathcal{W}$ is the set of all possible wrenches that can be applied to the part by the grasp and it can be used to evaluate the grasp. A wrench vector $\boldsymbol{w}_{i,j}$ is a stacked vector of a force $\boldsymbol{f}_{i,j} \in \mathbb{R}^3$ and torque $\boldsymbol{\tau}_{i,j} \in \mathbb{R}^3$ applied at the torque origin, often the object's center of mass:

$$\boldsymbol{w}_{i,j} = \begin{bmatrix} \boldsymbol{f}_{i,j} \\ \boldsymbol{\tau}_{i,j} \end{bmatrix} \in \mathbb{R}^6,$$

where indexes i and j represent the i-th contact point of the grasp and the j-th bounded force of linearized friction cone $\mathcal{F}_i$, respectively.

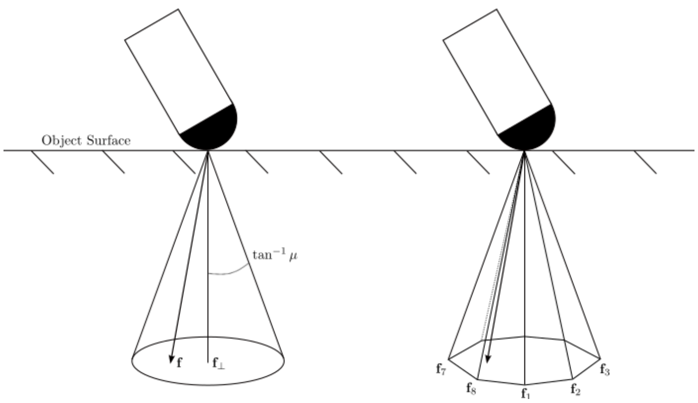


Figure 5. A friction cone and the corresponding pyramidal inner-approximation.

It can be rewritten as:

$$\boldsymbol{w}_{i,j} = \begin{bmatrix} \boldsymbol{f}_{i,j} \\ \lambda(\boldsymbol{d}_i \times \boldsymbol{f}_{i,j}) \end{bmatrix},$$

where $\lambda \in \mathbb{R}$ is the torque multiplier and vector $\boldsymbol{d}_i$ defines the position of contact point i with respect to the torque origin. Regarding the constant λ, it is arbitrary. However, a value of $\lambda = 1$ is common if the forces $\boldsymbol{f}_{i,j}$ are dimensional. In (Pollard, 1994), a value of $\lambda = \frac{1}{r}$ is used to ensure that the quality of a grasp is independent of object scale, where r is the maximum radius from the torque origin.

The *grasp wrench space* $\mathcal{W}$ is then defined as.

$$\mathcal{W} = \{\boldsymbol{w} \mid \boldsymbol{w} = \sum_{i=1}^{k} \sum_{j=1}^{m} \alpha_{i,j} \boldsymbol{w}_{i,j}, \quad \boldsymbol{w}_{i,j} = \begin{bmatrix} \boldsymbol{f}_{i,j} \\ \lambda(\boldsymbol{d}_i \times \boldsymbol{f}_{i,j}) \end{bmatrix}, \quad \sum_{j=1}^{m} \alpha_{i,j} \leq 1, \quad \alpha_{i,j} \geq 0\}$$

Unfortunately, the grasp wrench space $\mathcal{W}$ is cumbersome to compute in practice. Instead, the *grasp wrench hull* $\widetilde{\mathcal{W}}$ is used to characterize a grasp because it can be efficiently computed (with for example the Qhull program (Barber, Dobkin, & Huhdanpaa, 1996) and more importantly the property $\widetilde{\mathcal{W}} \subseteq \mathcal{W}$ holds by definition. The wrench hull $\widetilde{\mathcal{W}}$ is defined as.

$$\tilde{\mathcal{W}} = \{\boldsymbol{w} \mid \boldsymbol{w} = \sum_{i=1}^{k}\sum_{j=1}^{m} \alpha_{i,j}\boldsymbol{w}_{i,j}, \quad \boldsymbol{w}_{i,j} = \begin{bmatrix} \boldsymbol{f}_{i,j} \\ \lambda(\boldsymbol{d}_i \times \boldsymbol{f}_{i,j}) \end{bmatrix}, \quad \sum_{i=1}^{k}\sum_{j=1}^{m} \alpha_{i,j} = 1, \quad \alpha_{i,j} \geq 0\}$$

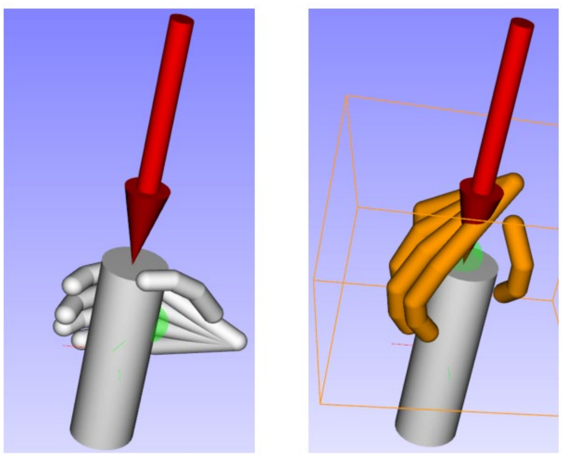
Two grasp quality metrics can be defined based on the definition of the grasp wrench hull $\widetilde{\mathcal{W}}$: *epsilon measure* and *volume measure* (Li & Sastry, 1988) (Miller & Allen, 1999). The epsilon measure is simply the radius of the largest 6D ball inside $\widetilde{\mathcal{W}}$. A grasp is in force closure if and only if the radius is greater than zero (i.e., the origin is contained in the interior of $\widetilde{\mathcal{W}}$). The epsilon measure is a worst-case metric because the radius represents the magnitude of the *smallest* external wrench that can push the grasp to its limits. Given a 3D object, at least three contacts are required for a grasp to be in force closure under a point contact with friction model. The volume measure is defined as the volume of $\widetilde{\mathcal{W}}$ and it is an average case metric. Given two grasps with the same epsilon measure, the volume measure can be used to differentiate between them. Unfortunately, the volume measure does not reflect the stability of a grasp (i.e., it's not guaranteed to be in force closure even if it has a larger volume measure than a stable grasp). Another difference between the epsilon measure and the volume measure is that the volume measure is invariant to the choice of torque origin, whereas the epsilon measure is not.

Grasp Planning

In this subsection, we describe our user-guided grasp planner that is able to synthesize and then evaluate a multitude of grasps quickly using the two grasp quality metrics from the previous subsection and then presents the stable grasps to the IMMA user.

Firstly, the IMMA user selects a suitable grip type among the ones listed in Figure 4 and then defines the approach direction that the hand must follow during the synthesis process by selecting a point on the surface of the part. Assume that we want to grasp the top of the cylinder in the left subfigure in Figure 6, then we can select a single point on the top base of the cylinder to define the approach direction. In the left subfigure in Figure 6, the resulting approach direction visualized as a red arrow that points in the opposite direction of the surface normal vector at the selected point. The approach direction can also be modified by rotating the arrow's tip around the selected point.

Secondly, grasps are automatically synthesized by letting the hand assume the open hand configuration in the neighborhood of the part and then approach the part following the approach direction such that the hand is aligned so that the unit length vector halfway between the y and z axes in the local coordinate system for the hand's Grasp Center Point (GCP) points in the approach direction. In Figure 3, the GCP coordinate system's x, y, and z axes are represented by red, green, and blue, whereas the origin of the coordinate system is enclosed inside a green sphere. To synthesize a multitude of grasps, we randomly sample the hand's rotation around the approach direction. The hand is moved towards the part until a collision between them is detected or the GCP is reached by the geometry of the part. In case of collision, the hand is moved away from the part until the collision is resolved (Vahrenkamp, et al., 2013). Next, the hand's fingers are closed one-by-one around the geometry of the part by interpolating the joint angles from the selected grip type's open hand configuration to its closed hand configuration. The resulting contact points between the fingers and the part are then used to compute both the epsilon measure and the volume measure. N.B.: A grasp is in force closure when its epsilon measure is greater than zero. In this way, many grasps can be quickly synthesized and the IMMA user only needs to select one of the stable grasps (e.g., the one in the right subfigure in Figure 6) at the end.



(a) Approach direction. (b) A stable grasp.

Figure 6. Use grasp approach direction to synthesize stable grasps.

Results

In this section, we present examples of grasp synthesis for a couple of objects using our user-guide grasp planner for the IMMA digital hands.

In the left subfigure in Figure 7, the Pointwise Shortest Distance method (Li, Kressin, Vajedi, & Carlson, 2017) is used to color the surface of the CEM box, where the red patches are the areas that are too close to the obstacles when the box is moved from the start pose to the goal pose. Instead, we select a point on a green patch during the assembly simulation to obtain an approach direction that points perpendicularly into the green patch as shown in the right subfigure in Figure 7. Next, we select grip type *Spherical Grip* and run the grasp planner for 60 seconds. The most stable grasp (i.e., the one with the greatest positive epsilon measure) among the resulting grasps is also shown in the right subfigure.

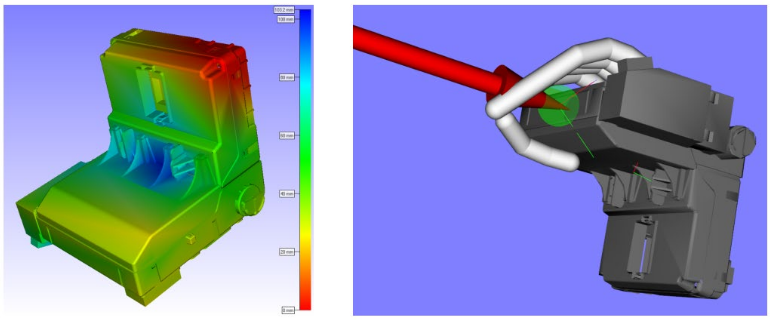


Figure 7. CEM box colored using the pointwise shortest distance method and a stable grasp.

In Figure 2, both Pointwise Shortest Distance and Environment Clearance are applied to color the surfaces of the tunnel console, where surface patches that can be easily accessed by a manikin hand are correctly rendered in blue by the Environment Clearance method as shown in the right subfigure. We select a point on a sloping edge of the tunnel console and then manually rotate the approach direction slightly so that its approximately points perpendicularly to the ground (assuming that the tunnel console is placed with its bottom on a table) as shown in Figure 8. Next, we select grip type *Cylindrical Power Grip* and run the grasp planner for 60 seconds. The most stable grasp (i.e., the one with the greatest positive epsilon measure) among the resulting grasps is also shown in the figure.

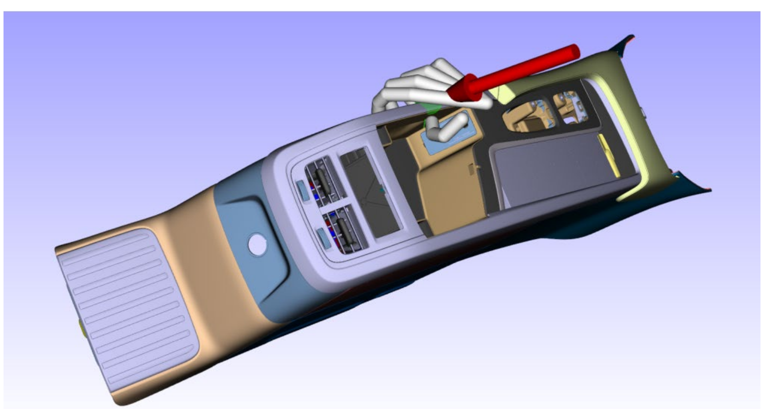


Figure 8. Volvo XC90 tunnel console and a stable grasp.

For a large object that requires at least two hands, it is not possible to find a stable grasp using a single hand. However, our user-guided grasp planner can still be used to synthesize good-looking grasps, where the resulting grasps can be sorted by the volume measure that does not reflect the stability of a grasp.

Discussion and Conclusions

We have demonstrated that our user-guided grasp planner is able to quickly synthesize a huge number of grasps for a given part so that an IMMA user can simply choose one among the grasps with the best grasp qualities instead of the previous time-consuming process of manual synthesizing a grasp by placing the hand at a suitable spot close to the part and then closing the fingers around it. Consequently, we believe that this user-guided grasp planning approach can significantly enhance IMMA's usability for assembly simulation experts. Future work will include adding support for a second hand to handle larger objects. We would also like to include a task-oriented grasp quality metric since both the epsilon measure and the volume measure are task-independent.

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