MAESTRO - a tool for interactive assembly simulation in virtual environments

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Abstract. We introduce MAESTRO, a Virtual Reality based assembly simulation tool that comprises physically-based modeling, haptic feedback and artificial support mechanisms. The focus of this paper is on the developed support mechanisms and the evaluation of the system. The experimental results show that all three features – haptics, physics, and artificial support – considerably improve user performance and user acceptance during the completion of assembly tasks in a virtual environment.

1 Introduction

During the last years, Virtual Reality (VR) has proven its potential for the visualization and manipulation of complex data like 3-D geometries generated by means of CAD applications. An interesting and promising area of application for virtual environments is assembly simulation. Though virtual environments can already profitably be integrated into engineers' daily work, there are still a lot of disadvantages in existing VR-based assembly simulation systems, requiring trained engineers for performing interactive simulations. Especially, the lack of satisfactory feedback mechanisms in existing VR-based simulation environments complicates execution of interactive manipulations of virtual objects. In detail, suitable modeling of user-object interactions, realistic simulation of object behaviour, and intuitive presentation of information are missing. During the last 2 years, we have been developing a software called MAESTRO (**M**ultimodal Inter**a**ction Techniques for Ass**e**mbly **S**imulation in Vir**t**ual Envi**r**onments), where, for the first time, the following features are combined in a single, comprehensive tool:

- Realistic, physically-based behaviour of virtual objects, including automatic calculation of the objects' inherent mechanical characteristics
- Integration of force feedback into the interaction with virtual objects, operating on a unique scene graph for both, graphics and haptics
- Artificial support mechanisms like sensitive polygons, virtual magnetism, and guiding sleeves

The focus of this paper is not to describe the single algorithmic approaches of the MAESTRO features in detail, but instead to give insight into the overall MAESTRO functionality, and to demonstrate by means of a system evaluation that the combination of all features can contribute significantly to a better user performance and user acceptance during the simulation of assembly tasks in a virtual environment (VE).

The remainder of the paper will start with a short survey of existing VR-based assembly simulation tools. In section 3, our approach is compared to other simulation systems. Furthermore the physically-based modeling and the haptics component of MAESTRO are briefly described here. Section 4 illustrates the developed artificial support mechanisms, and section 5 gives an overview of the MAESTRO hardware and software. Finally, section 6 evaluates the system by means of two experiments. The paper ends some remarks about future work.

2 A Brief Survey of Assembly Simulation in VE

Basically, available systems for interactive assembly simulation in virtual environments can be subdivided into knowledge/rule-based approaches and physically-based approaches.

R. Heger [1] introduced a knowledge-based system that allows an interactive execution of manual assembly tasks in a virtual environment. The system works with the concept of reference points, i.e., single vertices within the polygon models which can be placed at connection elements (e.g., screws) or target positions. For the single reference points, assembly-specific object characteristics are stored and take care that objects are placed automatically and exactly when the user approaches such a reference point.

A similar approach was chosen by M. Grafe [2] for a virtual construction system that uses basic elements. Functional nodes can be attached to single surfaces of these elements causing, e.g., a snap-in when two corresponding nodes are approaching.

B. Jung [3] describes a knowledge-based system that allows an interactive assembly of virtual basic elements to complex modules. Here, a polygonal and a logical description are stored in two separate knowledge databases. The first one contains object characteristics which are relevant to assembly, and which are represented by so called ports. The second one serves to describe a construction goal, i.e., a kind of plan how to create modules from single objects. This knowledge allows the system to recognize assembled objects as modules and, by inference from the knowledge database, to deduce the specific use of single elements within a module.

All three knowledge-based systems are using a tracked instrumented glove and 3-D mices as interaction devices and do not provide force feedback mechanisms. In the VADE system developed by S. Jayaram [4] and an assembly system introduced by M. Buck [5], bimanual interaction is included by means of two instrumented gloves. Both systems contain a physical, constraint-based approach to achieve a realistic object behaviour. For physically-based modeling, Buck uses polygonal models of lower complexity than for visualization. When two objects intersect, the objects are simultaneously presented to the user at their physically plausible positions and, in a wireframe representation, at their intersected positions. While in the system of Buck reaction forces are visualized as vectors, the VADE system should provide a real force feedback by means of an exoskeleton glove.

R. Gupta et al. [6] introduce an assembly simulation system that provides force feedback by means of two PHANToM Haptic Devices [7]. Here, the graphical representation of the scene and the physically, constraint-based modeling are completely separated. In contrast to all other systems mentioned here, the system of Gupta is restricted to two dimensions and does not support the use of immersive displays.

3 The MAESTRO Concept

MAESTRO combines a physically-based and a knowledge-based approach in order to profit from the advantages of both strategies, i.e., realistic object behaviour on the one hand and effective manipulation of virtual objects on the other hand. The inflexibility of rule- and knowledge-based systems is avoided here, because most of the necessary knowledge is generated automatically, and because only a few assembly-relevant rules are applied. Physically-based modeling (PBM) and artificial support mechanisms, based on priori knowledge about the assembly goal, are completed by haptic feedback functionality. Our approaches for PBM and haptics are only briefly introduced in the remainder of this section, whereas the support mechanisms will be described in more detail in the next section.

Physically-Based Modeling To achieve a realistic behaviour of virtual objects by means of physically-based modeling, mass, friction coefficient, centre of gravity, and inertia tensor of the virtual objects must be known. In MAESTRO, these inherent mechanical characteristics are calculated automatically from the polygonal description of the model geometry. Since the geometries can normally be easily exported from a CAD application, MAESTRO possesses a high flexibility. In principle, the problem can be reduced to volume determination of the polygonal models. Here, we have implemented and compared different exact and approximative algorithms [8].

Starting from the mechanical object characteristics calculated in step one, we have, in contrast to other systems (see section 2), preferred an impulse-based approach to a constraint-based approach, because it allows for a consistent methodical treatment of all kinds of contact between virtual objects. Most of the algorithms we have integrated here, are well documented in the publications of B. Mirtich and D. Baraff (see, e.g., [9–11]). Whenever possible, reactions to collisions are calculated algebraically in order to fulfill the real time requirements of interactive assembly simulations. In MAESTRO, numerical integration is only applied to the simulation of sliding motions. For recumbent contact situations, a simple, rule-based approach was found.

Haptic Feedback A severe deficit of today's systems for interactive assembly simulation is the lack of multimodal, especially force feedback. The few existing systems like those of Jayaram or Gupta (see section 2) operate with a redundant haptic scene graph in order to provide stability of the haptic rendering. In contrast to these systems, our approach is based on a single scene graph for graphics as well as haptics, thus dramatically reducing modeling costs and gaining a higher system flexibility. In order to achieve stability even without a haptic description of the scene, we are operating with an interim representation of contact situations. We will decribe this approach in detail in a forthcoming paper.

4 Artificial Support Mechanisms

In order to compensate for the problems which inevitably exist in VR-based assembly operations, arising from the non-exact modeling of geometry and behaviour of virtual objects as well as from inadequacy of available interaction devices, we developed and integrated artificial support mechanisms into MAESTRO. Figure 1 illustrates how the implemented mechanisms – guiding sleeves, sensitive polygons, virtual magnetism, and snap in – are assigned to the three classical phases of an assembly process.

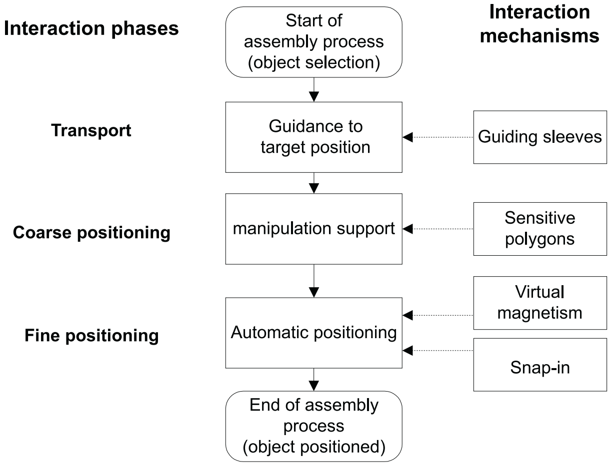

Fig. 1. Assignment of the integrated support mechanisms to the single interaction phases of an assembly process

Guiding Sleeves Guiding sleeves are a support mechanism that makes use of priori knowledge about possible target positions and orientations of objects. In the configuration phase of an assembly simulation with MAESTRO, the guiding sleeves are generated in form of a scaled copy or a scaled bounding box of the objects that are to be assembled, and then placed as invisible items at the corresponding target location. When an interactively guided object collides with an adequate guiding sleeve, the motion path necessary to complete the assembly task is animated as a wireframe representation. In addition, the target position and orientation is visualized by means of a semi-transparent copy of the manipulated object (see Fig. 2).

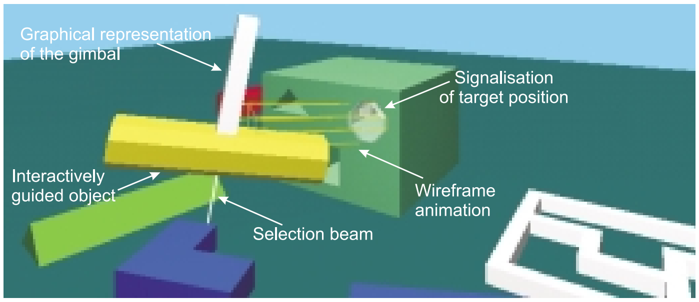

Fig. 2. Guiding sleeves support the user during the transport phase of an assembly task by means of a wireframe animation of the assembly path

Sensitive Polygons Sensitive polygons are created before simulation start and positioned at adequate positions on object surfaces. A function can be assigned to every sensitive polygon, which is automatically called when an interactively guided element collides with the sensitive polygon. We have designed sensitive polygons primarily to support the user during the coarse positioning phase of an assembly task. Among others, the polygons can be used to constraint the degrees of freedom for interactively guided objects. For instance, a sensitive polygon positioned at the port of a hole can restrict the motion of a pin to the axial direction of the hole and thus considerably facilitate the assembly task. In case of this classical peg in hole assembly task, MAESTRO creates a copy of the guided object, orientates this copy into the direction of the hole's axis, and switches the original object into a semi-transparent representation (see Fig. 3).

Virtual Magnetism In assembly procedures, it is often necessary to position objects exactly, i.e., parallel to each other at arbitrary locations, without leaving any space between them. Since in a virtual environment this task is nearly impossible to accomplish without any artificial support mechanisms, we developed the principle of virtual magnetism. The left part of Fig. 4 illustrates the effect of virtual magnetism on movable objects. As with sensitive polygons, virtual magnetism is an essential component of the the knowledge-based modeling of virtual objects' behaviour. In contrast to PBM and the other support mechanisms, a user must actively initiate it during the simulation, e.g., by a speech command.

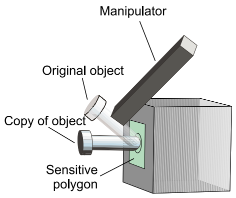

Fig. 3. Use of a sensitive polygon to facilitate the peg in hole assembly task

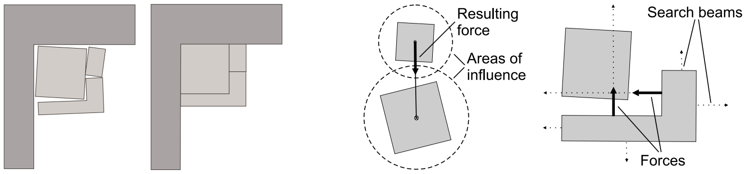

Fig. 4. Effect of virtual magnetism (left), and force components based on object distance and object surfaces

Before simulation start, an object's influence radius is calculated as a function of its volume. Whenever two of such influence areas overlap during the simulation, an attraction force is generated that consists of two components (see Fig. 4). The first component is calculated from the distance between the two objects' centers of gravity, and the second component is a function of polygon surfaces. To calculate the second component, a search beam starts from every polygon midpoint into direction of the surface normal. If such a beam intersects with a polygon of the other object, a force directed to the surface normal is created, which is proportional to the distance between the polygons. Finally, the sum of the to force components is applied to move the smaller object towards the larger one.

Snap-In As all other VR-based assembly simulation tools (see section 2), MAESTRO provides a snap-in mechanism for the final phase of an assembly process. The snap-in is activated when position and orientation difference between the guided object and the target location falls below a specific threshold.

5 The MAESTRO Prototype

Hardware Recently, we have accomplished a first prototype of MAESTRO, in which the force feedback system is a crucial component. We are using the PHANToM 1.5 from Sensable Technolgies [7], allowing a six degrees of freedom input and a simple force vector as output. Due to the rather small interaction volume of the PHANToM, we had to choose an indirect interaction paradigm, where the pencil-like manipulator ("gimbal") of the PHANToM is represented by a graphical counterpart in the VE (see Fig. 5), whose motions are adequately scaled. The PHANToM is connected to a PC that sends position and orientation data to and receives force data from the simulation computer via a 100 MHz Fast Ethernet.

In principle, MAESTRO can work together with any immersive display technology. In combination with the PHANToM, a table-like display is more suitable than a HMD or a fully immersive display like the CAVE. To accomplish the evaluation of the system (see next section), we visualized the scene on a display consisting of a horizontal and a vertical projection surface (”TAN HoloBench”, see Fig. 5).

To facilitate interaction, we have furthermore integrated speech recognition that allows the user to pick up and release virtual objects, or to activate support mechanisms like snap-in or virtual magnetism, by a few simple speech commands.

So far, MAESTRO has been implemented on a Sun Microsystems E450 (2 Expert3D graphics boards) and on a SGI Onyx2 (1 Infinite Reality graphics pipe) workstation, both capable of driving a HoloBench in stereo mode.

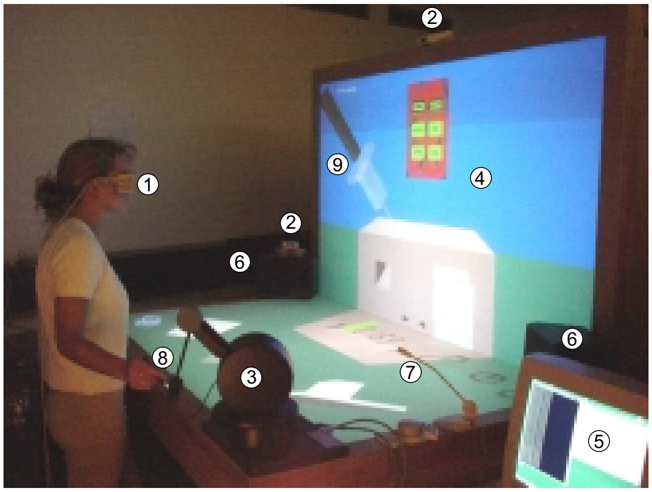

Fig. 5. Hardware setup of the MAESTRO assembly simulation system 1: Shutter glasses with receiver of electro-magnetic tracking system, 2: Infrared emitter for shutter synchronisation, 3: PHANToM Haptic Device, 4: Immersive display ”HoloBench”, 5: PC with haptics server and speech recognition software, 6: Stereo loudspeakers, 7: Microphone for speech recognition 8: Gimbal 9: Graphical representation of the gimbal with attached virtual object

Software MAESTRO is based on the cross platform VR software ViSTA (Virtual Reality Software University of Technology Aachen [12]) and is subdivided into three parallel processes: The graphical process is responsible for processing speech commands, applying interaction mechanisms, and rendering of the scene. It is typically running at a frequency of 30 Hz. The PBM process processes sensor values, force vectors and impulse information, recognizes collisions, and calculates physically plausible collision reactions with a sample rate of at least 250 Hz. Both processes run on different processors of the simulation computer and communicate with each other via shared memory. Finally, the haptics process runs on the PC at an update rate of 1200 Hz and communicates via UDP protocol with the simulation computer.

6 Evaluation

In order to evaluate the MAESTRO prototype, we have carried out experiments that are documented in detail in [8]. Two of these experiments shall be introduced and discussed here, with regard to effectiveness and user acceptance of the artificial support mechanisms, force feedback, and physically-based modeling. 12 right-handed subjects in the age of 24 to 31 participated at the experiments. They were asked to complete the required manipulation tasks quickly and accurately.

6.1 Experiment 1

The setup of experiment 1 is shown in Fig. 6. Two large and two small nails must be brought into the corresponding holes of a virtual block. The experiment consists of 3 phases: In phase 1, subjects had to complete the task in a "native" virtual environment, i.e., based on the 3-D visualization of the scene without any further modeling or feedback techniques. In phases 2 and 3 they were supported by guiding sleeves and sensitive polygons, respectively. Every phase was carried out twice. During the first trial, objects snapped in as far as the subject placed them into the target position below a certain tolerance. The trial ended when all objects snapped in, and the time subjects needed for completion of the task was measured. The second trial was interrupted automatically after a fixed amount of time, and the mismatches between the actual and the required object target positions were documented.

Results The results of experiment 1 show a significant time benefit with guiding sleeves in comparison to a native VE, and in turn a significant benefit when using sensitive polygons instead of guiding sleeves. In trial 2, the positions of the nails are significantly more exact for guiding sleeves than for native VEs (see Fig. 7). The subjects' judgement of task difficulty and quality of the user interface confirm the quantitative results (see Fig. 8). The snap-in mechanism has great importance with regard to the judgement of task difficulty. In case the snap-in is not available, e.g., because the target position of an object is not known, subjects judge the manipulation task as more difficult. In such cases, test persons regard the mechanisms of sensitive polygons and virtual magnetism as a useful alternative.

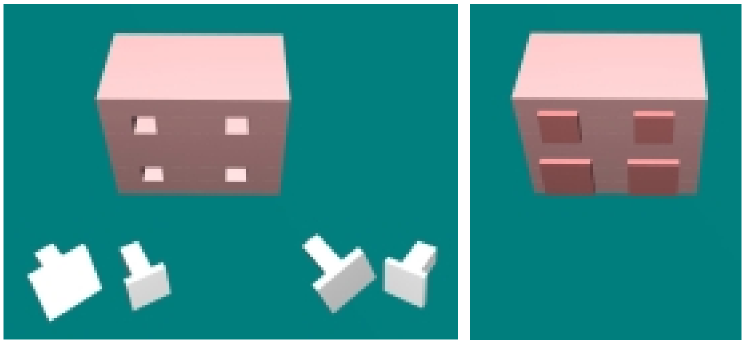

Fig. 6. Setup of experiment 1 – start (left) and target position (right) of virtual nails

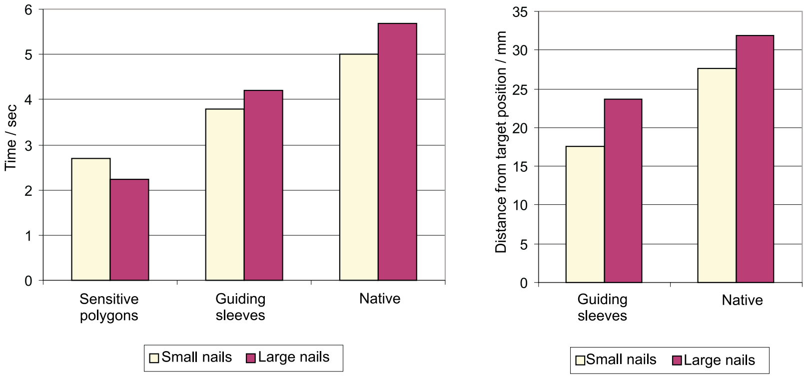

Fig. 7. Quantitative results of experiment 1 – placing virtual nails into a block. The left diagram shows the average amount of time needed until snap-in, the right diagram shows the average distance to the target position six seconds after start of the experiment.

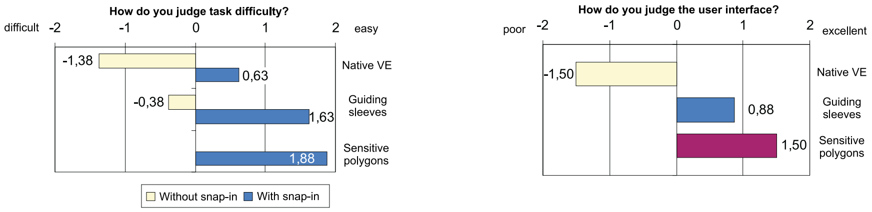

Fig. 8. Average judgement of task difficulty and user interface for experiment 1

6.2 Experiment 2

Figure 9 depicts the setup of experiment 2. Here, three virtual elements in form of the letters I, L, and T, have to be positioned into a frame. Again, the experiment consists of three phases. In the first phase, subjects had to complete the task in a native VE, where collisions between a letter and the frame are optically signaled by a wireframe presentation of the letter. During the second phase, the subjects were supported by haptic feedback. Finally, in the third phase, the subjects were asked to move the letters above their target positions and let them fall into the frame. The falling procedure, as well as the behaviour of the objects when touching the frame, have been physically modeled.

Fig. 9. Setup of experiment 2 – start situation (left) of virtual letters (I, L, T), and target position (right) in a virtual frame

Results A major result of experiment 2 is that the test persons had severe difficulties to complete the task in a native VE. They needed a dramatically larger amount of time than with support of haptics or PBM to position letter I. For letters L and T, it was even impossible to complete the task (see Fig. 10). An interview with the subjects revealed that in a native VE, they were not able to comprehend why and where exactly a collision appeared. As a consequence, they did not change their assembly strategy in a well directed manner and, instead, followed a trial and error principle, resulting in significant longer interaction times.

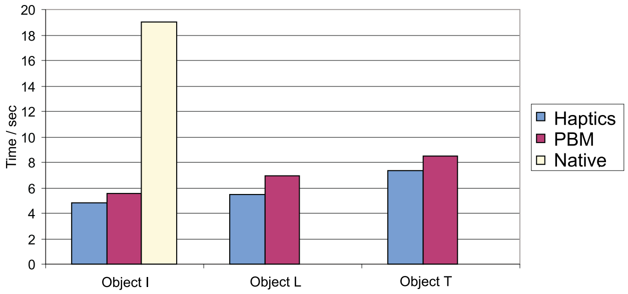

Fig. 10. Quantitative results of experiment 2 – placing virtual objects I, L, and T into a frame. The diagram shows the average amount of time needed until snap-in.

As in experiment 1, the subjects' judgements confirm the quantitative results. Both, haptic feedback as well as PBM, got a positive rating, although the test persons clearly preferred the haptic support to complete the task (see Fig. 11). Nearly all subjects praised the intuitive haptic representation of collisions. Furthermore, they pointed out that the simulated gravitational forces had a stabilizing effect onto their hand-arm-system. In a detailed judgement, haptics and PBM were nearly identically considered as important, realistic, helpful, and non-distracting (see Fig. 12).

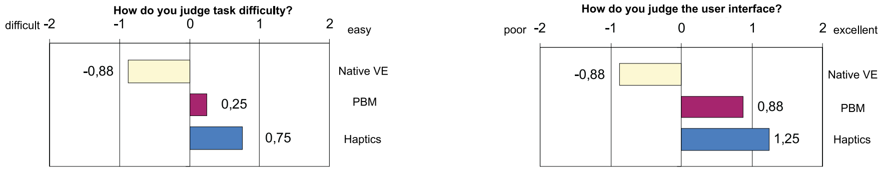

Fig. 11. Average judgement of task difficulty and user interface for experiment 2

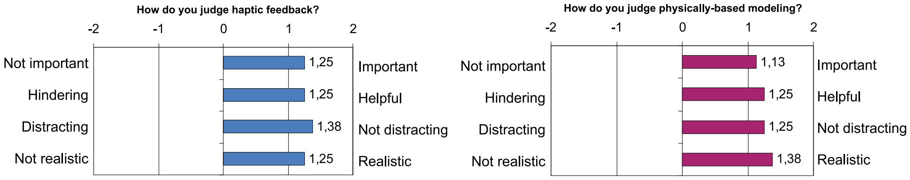

Fig. 12. Average judgement of haptic feedback and physically-based modeling (PBM)

7 Future Work

Since MAESTRO starts from the polygonal representation of a scene which can easily be exported from most CAD systems, and since most parameters needed for object behaviour, haptics, and artificial support mechanisms are calculated automatically before simulation start, MAESTRO is more flexible than most other assembly simulation systems. This benefit of a high flexibility comes along with the drawback, that MAESTRO can only handle virtual scenes of rather low complexity. The collision detection update rate is crucial to the quality of physically-based modeling and the stability of haptics. Since in MAESTRO, collision detection and all modeling are based on the polygonal object representation, the system performance is very sensitive to the number of polygons in the scene. In order to make MAESTRO applicable to assembly simulation scenarios that are relevant for industrial applications, we are working on the integration of improved collision detection algorithms and on a comprehensive parallelization of the MAESTRO software architecture.

The MAESTRO prototype makes use of a force feedback device that merely produces a force vector. However, for many manipulation tasks it is desirable to adequately present torques or even to stimulate the whole hand-arm system.

The MAESTRO algorithms are prepared for that, and in the meanwhile, haptic devices are available and should be integrated into the prototype, which produce six degrees of freedom forces.

Besides graphics and haptics, 3-D acoustics could furthermore improve the realism of an interactive assembly process and lead to a better user performance and acceptance. Therefore, we just started to work on an integration of binaural acoustics technology into MAESTRO. Here, we follow an innovative approach that is based on only two loudspeakers, producing a stable binaural sound even when the user moves in front of the HoloBench.

A considerable extension of MAESTRO's functionality is still necessary to make it attractive for real life industrial applications. Future versions of MAESTRO should allow bimanual interaction, the use of virtual tools like screwdrivers and wrenches, and provide a real-time, realistic modeling of deformable objects. Furthermore, it is highly desirable to establish a bidirectional interface between MAESTRO and product data management systems (PDMs) in order to integrate VR-based assembly simulation into the overall production process.

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