Generation of Assembly Process Plans and Associated Gilbreth Motion Study Data

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Abstract

Virtual assembly systems to date have tended to rely on pre-defined associations with a set of operation as a means to automate the generation of assembly plans. Even with the introduction of glove-based devices and wands as interactive manipulation implements, these systems still rely on the classical assembly techniques such as proximity snapping, constraint and axis-assisted co-location to mate components together. Consequently, data relating to associated procedural and final operational assembly information becomes obscured. The loss of such precise details and fitting operations has implications downstream, for example, when robotic assembly instructions or manual instructions are required. This paper investigates the use of a free-form haptic virtual environment to generate assembly plans based on the user-object interaction information obtained during the virtual assembly. Using Gilbreth's time and motion study this paper reports how such a classical method has been successfully implemented in identifying assembly operations, such as positioning and assembling. By analysing the therblig units associated with a process, unneeded movements can be eliminated to optimise a task and to generate an assembly process plan.

Keywords: Assembly plans, assembly operations, virtual assembly, haptics, chronocyclegraphs, therbligs.

1 Introduction

Assembly is an important process in product development and accounts for a large proportion of the manufacturing cost (Shimon et al, 1997). An important consideration in an assembly process is the definition and quantification associated with the sequence of operations and time required. A complete assembly plan includes a set of instructions describing the sequence of operations, joining methods and materials, tooling, fixturing and relevant quality assurance procedures. Computer Aided Assembly Planning (CAAP) systems have emerged as a tool to accelerate the planning of building a component, but have not, in general, been successful even when the design has been carried out using a modern Computer-Aided Design (CAD) system (Dewar et al, 1997). One of the main reasons for this lack of success is that assembly is dependent on a great deal of expert knowledge which has proved very difficult to formalize. In order to improve the efficiency of the assembly planning, the automation of the assembly planning process is a research issue that has become popular in the last years.

The use of virtual assembly environment tools has been studied more recently in order to provide three-dimensional input and stereoscopic viewing to perform, verify, and plan the assembly of components, and for training purposes. Virtual Reality (VR) environment has the potential to offer a more natural, powerful, economic, flexible platform than a traditional engineering environment to support assembly planning, (Ye et al, 1999, Brough et al 2007).

Several investigations into virtual environments for design and assembly tasks have been carried out for many years. Many of these virtual manufacturing interfaces make extensive use of advanced computer graphics. However, screen-based CAD/CAM, which only stimulates the visual senses, has made actual physical contact during product development an increasingly rare occurrence. Engineers still find the sensation of handling a physical prototype or experiencing manufacturing processes useful and intuitive; indeed, hands-on experience reinforces the understanding of the physical, operational and visual aspects of engineered items (Lim et al, 2007). To facilitate this, the sense of touch and kinesthesia have been introduced in computer based design and manufacturing environments by using haptic devices, (for instance, Howard et al, 2007; Garbaya et al, 2007). A haptic device enables manual force-feedback interaction with virtual environments or teleoperated remote systems. Force feedback haptic devices generate computer-controlled forces to convey to the user a sense of the feel of the virtual environment and objects within it. Designers can acquire the benefits of a digital process and yet continue to be involved with tactile design modelling (Sener et al, 2002). Force feedback devices, such as SensAble's Phantom Haptic Device (Massie and Salisbury, 1994) has been a research topic in the development of advanced computer-aided design systems, gaming and other simulated environments. However, despite this potential of having force feedback devices, very little work has been done towards the development of haptic human-computer interface for assembly process planning. While most of the published work on VR applications with force feedback shows the benefits of haptics, they do not discuss the use of the information developed within simulations in the virtual environment to generate assembly plans. Generally, haptics remains as a facilitator in guiding spatial exploration rather than as an output of task planning and in more general terms, manufacturing information. The cognitive procedures related to assembly tasks during user interaction can provide information to generate the assembly procedures to construct a component.

This paper introduces a new free-form haptic assembly planning system which allows the user to perform virtual assemblies with the sense of touch and kinaesthesia in a virtual environment. The system tracks the user-object interaction during the performance of the virtual assembly. This data obtained is plotted as a time-dependent profile describing motion together with position, orientation and velocity. Using Gilbreth's time and motion study, the system generates assembly procedures that can be used for the real assembly of the component. Unnecessary movements can also be identified and therefore the assembly plan is optimized.

2 Literature review

The use of immersive haptic interfaces to enhance the design and manufacturing process has increased greatly in the last years. Various researchers have investigated sense of presence measurements, simulation validity and human performance, in an effort to assess the effectiveness of force-feedback virtual reality applications. A classic example relates to peg-in-hole insertion operations. Rosenberg (1994) carried out an empirical study where participants were asked to execute a peg insertion task through a telepresence link with force-feedback. The results indicated that human performance was significantly degraded when comparing telepresence manipulation to direct in-person manipulation. However, by introducing abstract haptic overlays into the telepresence link, operator performance could be restored closer to natural in-person capabilities. Gupta et al (1997) investigated the benefits of multimodal simulation using virtual environment (VE) technology for part handling and insertion compared to conventional table-based methods, as presented by Boothroyd et al (2002). The results showed that assembly task completion time increased in proportion to the complexity of the assembly operations required. However, the measured times were roughly double those required to carry out the operation in the real world. Although they employ two haptic arms their study is restricted to 2D simulations of the insertion operation. Significantly for the work reported in this paper the authors speculate that one of the contributory factors to task completion time was the lack of co-location. Unger et al (2001) described an experimental arrangement for comparing user performance during a real and virtual 3D peg-in-hole task. The task required inserting a square peg into a square hole via a 6 DOF magnetic levitation haptic device and visual feedback. The goal was to understand human manipulation strategies. Bayazit et al (2000) reported that the lack of truly cooperative systems limits the use of haptic devices involving human operators and automatic motion planners. They presented a hybrid system that uses both haptic and visual interfaces to enable a human operator and an automatic planner to cooperatively solve a motion planning query. By manipulating a virtual robot attached to the Phantom haptic device a sequence of paths were generated and fed to the planner. Haptic interaction comprised of tracking user motion, collision detection between haptic probe and virtual objects, computing reaction forces, and force rendering. An obstacle-based probabilistic roadmap method was used in conjunction with a C-Space toolkit to filter the haptically generated paths and generate collision-free configurations for the robot.

The sensory feedback capability of haptics lends itself naturally to tasks that require manual manipulation. Adams et al (2001) conducted experiments to investigate the benefits of force feedback for VR training of assembly tasks. Three groups of participants received different levels of training (virtual with haptics, virtual without haptics, and no training) before assembling a model biplane in real world environment. Their results indicated that participants with haptic training performed significantly better than those without. The HIDRA (Haptic Integrated Dis/Re-assembly Analysis) researched by Coutee et al (2001) is a test bed application focused primarily on simulation of assembly procedures with force-feedback. Their intention was to provide a development perspective relevant to haptically enabled simulations. The research efforts of Seth et al (2005) fall into the similar assembly/disassembly category of analysis via visualisation with haptic force feedback. These reported examples are particularly useful for applications that provide tactile information regarding assemblability at the design stage. However, there is little evidence of data logged in order to output assembly instructions.

Recent research points towards developing architectures for collaborative haptic virtual environments (CHVEs). A VR assembly application called Virtual Assembly Design Environment (VADE) was developed to model parts behaviour by importing data from CAD software (Jayaram et al 1999) but without any force calculation. Some years later, the VADE system was extended to support the bouncing of parts when they collide with other parts (Wu 2003). Wan et al (2004) and Zhu et al (2004) created a Multi-Modal Immersive Virtual Assembly System (MIVAS) which allows the user to feel the size and shape of a part by providing force feedback by means of a CyberGrasp™ haptic device. Iglesias et al (2006) Collaborative Haptic Assembly Simulator (CHAS) is one reported work that investigates assembly/disassembly simulation of mechanical components in a collaborative virtual environment. The system has the potential to manage large assemblies; unfortunately, they do not appear to have stored and managed the history of movements. A review by Ferreira and Mavroidis (2006) on the application of haptics in nano robotics illustrates the advancement of VR and haptics. However, only the exploratory influence and the associated sensory advantages of tactile feedback are reported. A desktop haptic virtual assembly system has been proposed by Howard and Vance (2007). The proposed system has been designed as a design tool to evaluate assembly operations with some limitations such as the accuracy of the physical simulation between colliding geometries.

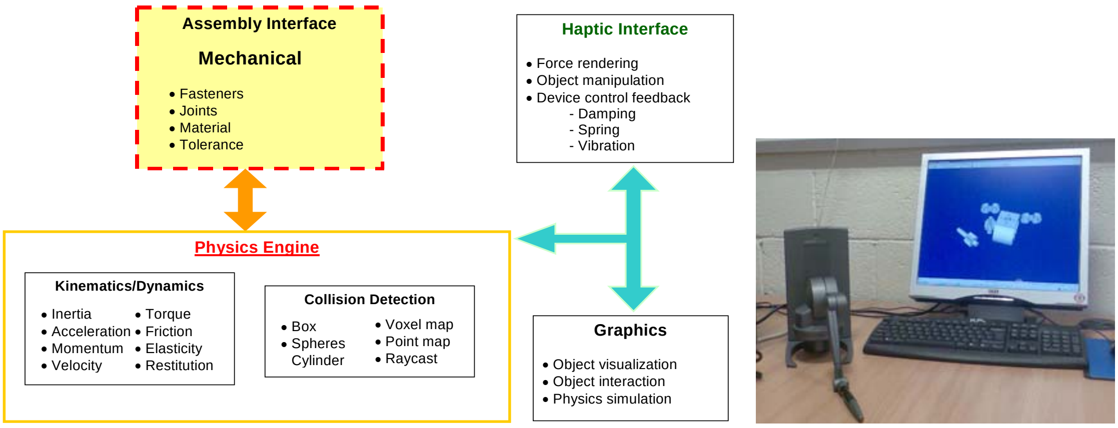
While most of the published work on VR assembly applications with force feedback shows the benefits of haptics, they do not discuss the automatic generation of qualitative information derived from assembly plans (syntax or semantics) developed within simulations in the virtual environment. Moreover, CAD-based assembly operations generally rely on the mating, aligning and/or offsetting of the regular faces of each of the mating parts.

Generally, haptics remains as a facilitator in guiding spatial exploration rather than as an output of task planning and in more general terms, manufacturing information. The objective of this work is to extrapolate the cognitive procedures relating to assembly tasks (and even tacit exploration of the virtual components) during user interaction will provide information to better a product's design for manufacture and assembly (DFMA).

3 System overview

HAMMS (Haptic Assembly, Manufacturing and Machining System), has been developed as a test bed to investigate the user interactions and response while performing various engineering tasks in a virtual environment. The systems' architecture is presented in Figure 1b.
The hardware comprises a Phantom haptic device for interaction with the virtual environment, along with a pair of CrystalEyes® stereoscopic glasses for stereo viewing if required (Figure 1b). The application is coded in C++ and comprises three key elements:

- Haptics Interface: Sensable Technologies OpenHaptics® Toolkit (Sensable, 2008), which provides device control for the Phantom Desktop and Omni, and supports polygonal objects, material properties, and force effects.
- Graphics Interface: The Visualization ToolKit (VTK, 2008) is used for rendering graphics, image processing, and visualization.
- Physics' Interface: AGEIA PhysX™ (AGEIA, 2008) technology provides the physics engine that includes an integrated solver for fluids, particles, cloth and rigid bodies.



(a) Schematic (b) Hardware

Figure 1. HAMMS hardware and schematic.

The HAMMS environment allows objects to have their physical state modified and user/device/object interactions logged with the results displayed in real-time as shown at the bottom of the graphical user interface (GUI) in Figure 2. The basic logged data comprises position, orientation, time stamps, velocity and an object index (or identifying number). The term *therblig* (Price et al, 1990) is used in the study of motion economy in the workspace. A total of 18 therblig units represent a set of fundamental motions required to perform a manual operation: Search; Find; Select; Grasp; Hold; position; Assemble; Use; Disassemble; Inspect;

Transport loaded; Transport unloaded; Pre-position for next operation; Release load Unavoidable delay; Avoidable delay; Plan; and Rest to overcome fatigue.

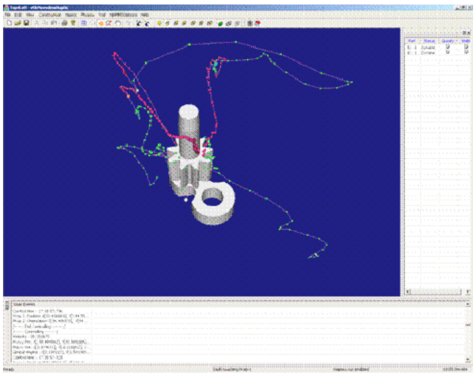


Figure 2. HAMMS user interface

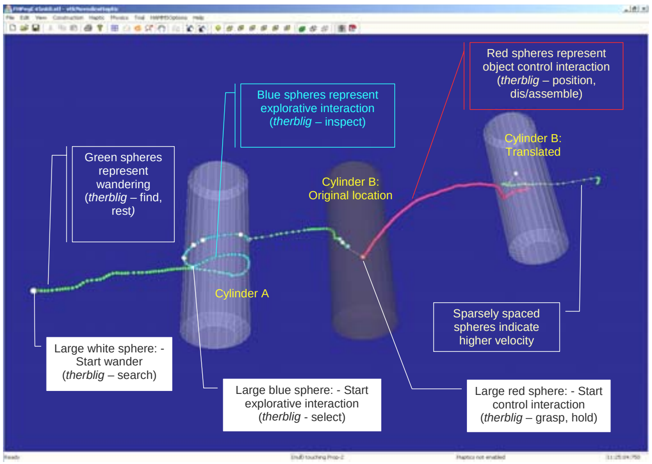


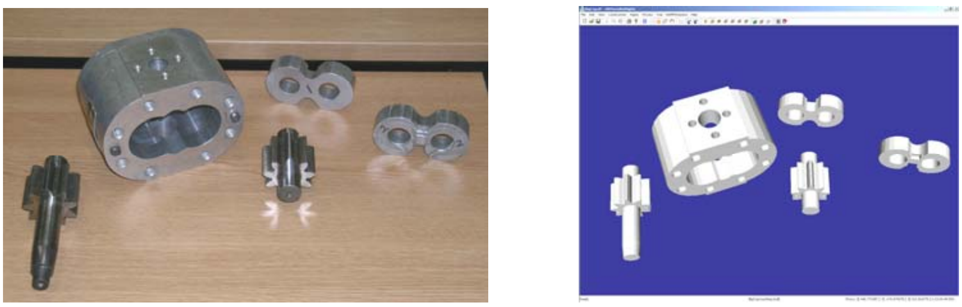
Figure 3. HAMMS colour coded therbligs.

Figure 3 illustrates the colour-coded therblig units adapted by HAMMS and its association to the logged data. To visualize the data stream, large spheres are used to signify the start of an event, while smaller contiguous spheres indicate the direction, speed, and location of exploration or controlled displacements. Green indicates search, find or rest. Blue represents selection and inspection. Red identifies control events such as grasping, holding, translation, dis/assembly operations. Velocity changes are indicated by the separation of the spheres, i.e. sparsely spaced spheres equate to higher velocity. The line joining all spheres is referred here as the motion-time-line (MTL). More details about the HAMMS system can be found in Ritchie et al (2008).

4 Methodology

To identify assembly operations an experiment was performed according to the following methodology:

1. Component CAD models - these must have the dimensions and tolerances similar to the actual component, i.e. a gear pump in this case (Figure 4).
2. Perform the assembly of the component in the virtual environment.
3. Identify assembly procedures from the logged data.
4. Perform assembly of the physical gear pump.
5. Compare and correlate information obtained during virtual assembly and physical assembly.



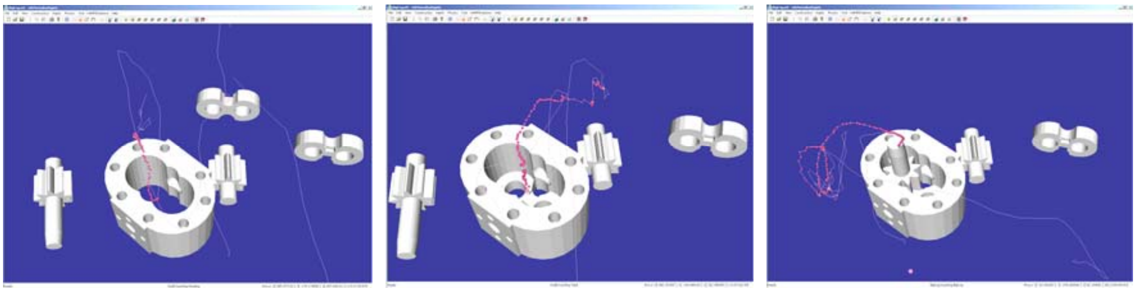
(a) (b)

Figure 4. Gear pump: components (a) Actual (b) Virtual.

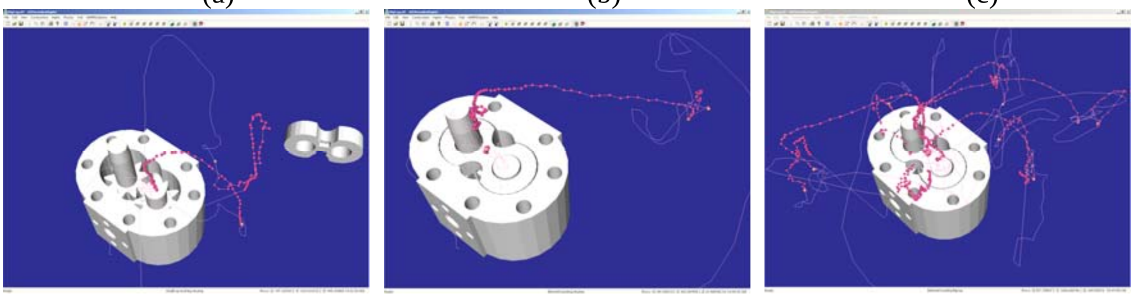
5 Results and discussion

To demonstrate the effectiveness of HAMMS and the data log parser, a group of participants were tasked to carry out both physical and virtual assembly of a gear pump comprising five components (housing, 2 bushings, a large cog and a small cog, Figure 4). The overall dimensions of the pump are 14.5 × 11 × 17 cm.

It is important to note that HAMMS is an unconstraint virtual assembly environment. CAD models uploaded may not be well-ordered before the assembly. In contrast to most CAAP systems HAMMS does not rely on proximity snapping, object-object co-alignment and other forms of programmatically assisted assembly functions. Instead HAMMS relies on the physical connotation that once a component is assembled, its geometry is constrained by the surroundings. As the rigid body comes to rest its dynamics are altered to 'kinematic' forming the 'joint' associated to the subassembly. Figure 4b shows the HAMMS virtual layout.



(a) (b) (c)



(d) (e) (f)

Figure 5. Virtual assembly: (a) reposition housing (b) assemble bushing (c) assemble large cog (d) assemble small cog (e) assemble bushing (f) complete assembly chronocyclegraph.

The virtual assembly begins with the repositioning of the housing (Figure 5a). Each individual assembly procedure (i.e. intent, motion and time) can be logged by the system and displayed as shown in Figures 5. Figure 5f shows the complete assembly chronocyclegraph illustrating how the participant manipulated the parts in order to complete the assembly task.

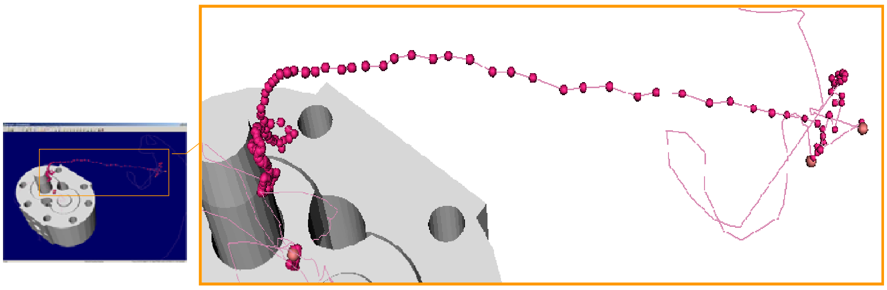


Figure 6. Chronocycle of control therblig units and motion time line (MTL).

The sparsely separated red spheres in Figure 6 infers speed and confidence of object interaction in HAMMS while close proximity spheres indicate careful orientation and final positioning associated to the intent of an assembly procedure. Additionally, the MTL length, shape and trajectory can also be used to detect user intent or confidence during the assembly.

The logged data from the virtual assembly process is stored as a text file which is then used to extract and generate the assembly plan. This file contains information of the therblig units associated with the virtual assembly process. Since HAMMS logs every operation performed by the user, the text file can be huge. For this purpose, an automatic data parser has been developed to identify and extract particular assembly operations as described by the therbligs units. The parser also allows the filtering of unnecessary assembly motions for example, when the user is just wandering or when the user made a mistake during the assembly. Figure 7 details the assembly of the small cog part. The results clearly show that both the chronocycle data and the logged file can be used to identify individual assembly tasks and motions performed by the user during the assembly. These assembly details can further be used to automatically generate assembly plans associated to physical operations. Figure 7 also shows the correlation between the virtual and physical assembly operations as extracted by the parser.

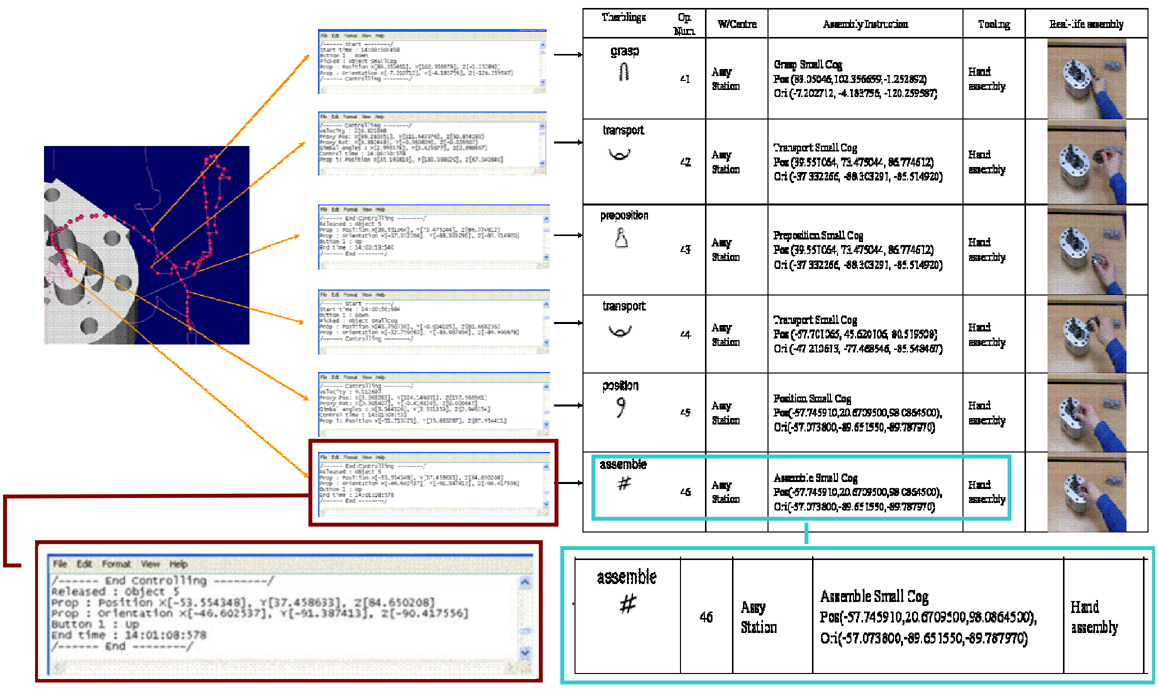


Figure 7. Identification and extraction of assembly operations from assembly planner logging.

The physical assembly of the pump was carried out using the same layout of the parts depicted in the virtual environment (Figures 4). It has to be mentioned that since the haptic virtual assembly environment currently uses just one haptic arm, the real-life assembly was performed with just one hand in order to compare both assembly processes under the same conditions. Time measurements were taken while performing the assembly operations from the physical assembly.

A more general process plan can also be generated from the logged data as shown in Figure 8, which also contains the assembly time obtained during the manual assembly process of the gear pump. Note that the position and orientation of each component in Figure 8 correspond to the final assembly location, and that the assembly process in real-world is faster compared to the virtual environment.

HAMMS TRIAL ASSEMBLY PLAN

Op. Num.	W/Centre	Assembly Instruction	Tooling	Assembly Time Virtual (s)	Assembly Time Real (s)
10	Assy Station	Assemble Housing Pos(58.4883300,57.9209000,203.717230), Ori(-45.441740,-63.667560,-67.873010)	Hand assembly	6.961	3.0
20	Assy Station	Assemble Bushing Pos(-38.544190,22.1121600,42.7273800), Ori(55.8205900,-89.920540,89.9831100)	Hand assembly	14.672	12.0
30	Assy Station	Assemble Large Cog Pos(-45.852190,19.6320600,74.7069200), Ori(-24.664120,-86.972570,-89.210800)	Hand assembly	9.672	5.0
40	Assy Station	Assemble Small Cog Pos(-57.745910,20.6709500,98.0864500), Ori(-57.073800,-89.651550,-89.787970)	Hand assembly	12.719	6.0
50	Assy Station	Assemble Bushing Pos(43.4192370,75.5965990,157.523040), Ori(-55.059900,83.3759800,-95.860880)	Hand assembly	17.797	9.0

Figure 8. Assembly plan automatically generated from the virtual assembly logged data.

6 Conclusions

The notion of identifying assembly states associated to a set of procedural tasks has been successfully demonstrated using an unconstraint (free-form) haptic assembly planning system, data logging and data parser. It has been shown that by analyzing the chronocycle graphs and logged data, assembly operations can be identified and extracted to generate the assembly plan. Moreover, assembly operations can be optimised by eliminating unnecessary movements performed by the user during the virtual assembly of the component. Thus, precise assembly plans can be automatically generated with the proposed system and be used to perform the real-world assembly.

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