The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

An Enhanced Haptic Assembly Simulation System for the Efficiency of Assembly Tasks

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Abstract— **This paper describes an enhanced haptic assembly simulation system, in which an optimal assembly algorithm is used to allow haptic interactions and traditional assembly sequence problems. The optimal assembly algorithm provides optimal paths for haptic guidance as well as an assembly sequence of the parts to be assembled. The performance of the given assembly schemes were simulated and analyzed using a haptic assembly system. Experimental results showed that the haptic-path sequence-guidance (*HSG*) mode gave the best performance improvement in terms of accumulated assembly time (28.56%) and travel distance (15.64%) compared to the unguided mode, while the sequence-guidance (*SG*) mode alone increased performance by 16.91% for assembly time and 11.66% for travel distance. The experimental results were analyzed by the sub-tasks of gripper selection, inter-part movement, and part assembly which showed the effectiveness of the optimal assembly algorithm.**

I. INTRODUCTION

Assembly planning can be simulated by means of virtual reality (VR) technologies to increase the efficiency of a real assembly process. In this way, potential problems in a given assembly scheme can be predicted by a user who may be able to suggest alternative methods in virtual environments (VEs). Since physical objects are represented as virtual objects inside VEs, real objects are not necessary for the simulation of a process. From this point of view, VR technologies have definite benefits in terms of cost and time.

Several VR-based applications for assembly planning purposes have been proposed. Jayaram *et al.* [1] developed VADE (Virtual Assembly Design Environment), a VR-system which is capable to evaluate the assembly planning for design and manufacturing. Yang *et al.* [2] and Yao *et al.* [3] have developed successful VR-based simulation systems which feature interactive constraint recognition and parts paths to assist the virtual assembly work. Through these systems, assembly sequence planning can be established after the assembly planner conducts several assembly simulations to verify the overall process of the specific assembly work. Ye *et al.* [4] and Chryssolouris *et al.* [5] discussed the performance of VR-based assembly planning systems based on assembly time evaluation. They concluded that a VR-based assembly planning system improves the performance.

To improve more effectively the performances of a virtual assembly simulation, the system itself can have intelligent algorithms as well as object tangibility so that the users are able to optimize the assembly tasks with realistic manipulation. Through haptic interfaces, users can have a sense of tangible reality of the virtual objects they interact with in VEs [6-7]. Active haptic guidance as well as object tangibility can be applied not only to medical haptics [8], a hand-write training [9] but also to a virtual assembly/disassembly system [10]. The active haptic guidance can enhance the efficiency of complex assembly tasks during a virtual assembly/disassembly system. For intelligent assembly planning, several researches [11–13] describe various techniques to achieve the optimal A/D (Assembly and Disassembly) sequence. In those methods, the number of gripper exchanges and the number of orientation changes were typically the basis for determining an optimal solution through an evaluation process. However, optimal assembly algorithms presented in the past did not consider the path for parts assembly, which is necessary for haptic guidance simulation/training. In results, most of VR assembly planning systems does not simultaneously provide sufficient object tangibility for active assembly help and the best assembly conditions by optimal assembly schemes. Especially, it is difficult to find evaluation results of optimal assembly algorithms with real experiments by a user except numeric simulations. To cope with these problems, we suggested a new assembly algorithm [15], which can generate simultaneously optimal paths as well as an optimal assembly sequence for a haptic guidance application. Furthermore, it is necessary to develop a virtual assembly simulation system so that an assembly operator can simulate the process of moving parts through optimum results [15].

In this paper, we describe an enhanced haptic assembly simulation system with optimized haptic paths and sequences. The proposed simulation system allows users to use a haptic interface in an A/D simulation, and allows a user to be effectively guided by an optimized haptic path and an optimal sequence. In this research, our main objective is to enhance the assembly works by the optimal assembly algorithm while

Manuscript received on March 1, 2009. This work was supported in part by the Korea Research Foundation Grant funded by the Korean Government (MOEHRD) (KRF-2005-005-J09902) and supported by 2nd stage BK21 (Brain Korea 21), R&D program of the Korea Ministry of Knowledge and Economy (MKE) and the Korea Evaluation Institute of Industrial Technology (KEIT). [2008-S-031-01, Hybrid u-Robot Service System Technology Development for Ubiquitous City.

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the haptic sensation is used as a means to increase the user's reality of virtual object and to prove the effectiveness of the suggested system through extensive user studies. For these purposes, we develop the enhanced haptic assembly simulation system in Section 2. Section 3 describes the optimal assembly algorithm for virtual assembly simulation. Section 4 describes user studies of a virtual assembly simulation, while Section 5 and 6 contain the result, evaluation, and discussions of user studies. Finally, we concluded our works and discussed the future works on Section 7.

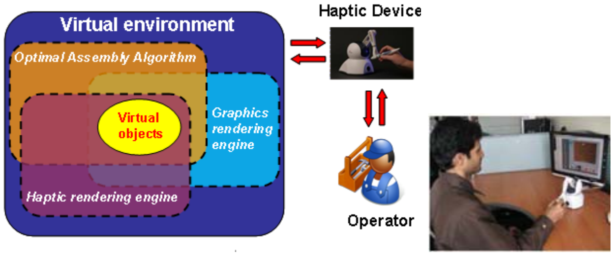


Fig. 1. Virtual assembly simulation system overview

II. ENHANCED HAPTIC ASSEMBLY SIMULATION SYSTEM

A. System Overview

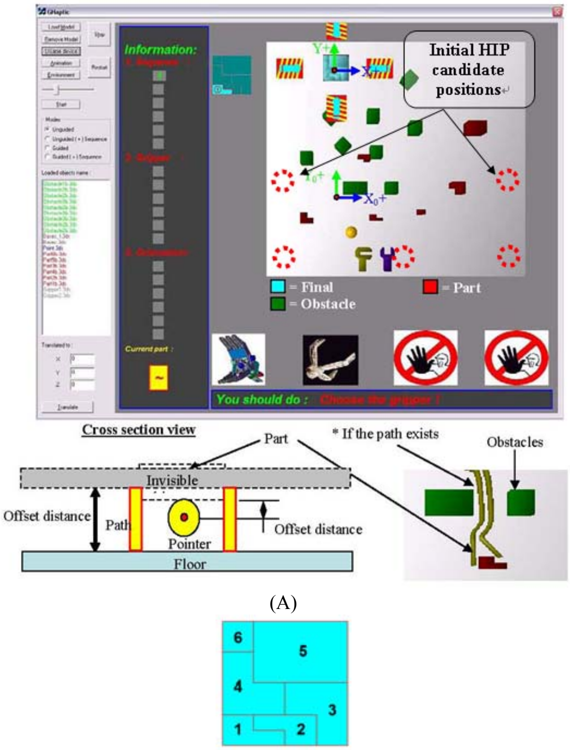
Our enhanced haptic assembly simulation system was built to take the benefits of virtual assembly simulations. The proposed system consists of a VE, a haptic device, and a user, as shown in Fig. 1. The VE includes manipulated objects (*i.e.*, virtual objects inside the VE), a graphics engine, and a haptic rendering engine. The files for manipulated objects are generated using a CAD software package and converted to object files so that they can be read by the graphics engine.

B. Virtual environment for assembly simulation

The VE for the assembly simulation consists of obstacles, parts in initial positions, final position marks, and suggested paths, as shown in Fig. 2.A. All the objects in the VE are virtual objects. The existence of virtual objects in the VE depends on several modes of assembly simulation that will be explained in Section 4. Even though the workspace is three-dimensional (3D), the assembly task is based on planar assembly with the final arrangement of parts, as shown in Fig. 2.B. To add a constraint for user movements in the *Z+* direction (toward the user's face), an invisible object is placed parallel to the floor at some offset distance (Fig. 2.A). Thus, the pointer can move only in the space between the floor and the invisible object. This scheme was chosen due to the special assembly case which is limited to planar assembly (2D). Adding constraint on Z+ direction makes user motion nearly planar motion (X, Y), which will allow easier analysis with the absence of user motion on Z+ direction

C. Haptic Interfaces

The user communicates with the VE using Sensable's Phantom Omni, a 3-DOF haptic device that provides six inputs (force and torque components) and three outputs (force components). In the VE, the haptic interaction point (HIP) is represented by the user-controlled pointer that is represented as a sphere. Since we use only point-to-mesh haptic rendering, users can feel a haptic sense through the pointer. When the user's HIP reaches the region of a part's initial point, a snapping mechanism is activated to attach the part to the HIP. At the same time, the center point of the manipulated object is automatically located in line with the HIP at some offset distance, as shown in Fig. 2.A.



(A)

(B)

Fig. 2. GUI components and VE simulation (unguided mode)

D. Haptic Rendering Software

We used the CHAI3D application programming interface (API) [14] for the graphics and haptic rendering engines. CHAI3D provides the most basic functions for developing haptic applications, including collision detection and haptic rendering. The graphical user interface (GUI) was designed to provide an interface between the operator and the VE (Fig. 2). The operator can manipulate objects in a window that contains the virtual assembly scheme. The haptic rendering loop runs at 1 kHz.

E. System Algorithm

The system consists of two processes: a real-time process and an offline process. The offline process deals with assembly optimization. The data needed for an optimal assembly algorithm are the part geometries and the grippers associated with each part. The real-time process includes a haptic rendering loop and an assembly procedure. The haptic rendering loop provides haptic feedback during the simulation process to make all virtual objects tangible. The assembly procedure ensures that the assembly task is performed with an optimal assembly path and sequence.

III. OPTIMAL ASSEMBLY RESULTS FOR ASSEMBLY SIMULATION

The subject case is to assemble 2D rectangular-shaped assembled parts which consist of 6 parts. It is assumed that each part has its own grippers list, initial position, final position, and assembly direction. Our optimization problem consists of finding the optimal sequence that brings the less number of orientation and gripper exchanges, and also appropriate repulsive force value satisfy the assembly rules. Optimization process based on optimal assembly algorithm [15] was used to construct the path for the haptic guidance and the assembly sequence that will be suggested to the user. The cost value was calculated based on the number of orientation changes (w_1), the number of gripper exchanges (w_2), and the actual path distance of each part (w_3). The path planning is based on the potential field method of which the repulsive force is used to have an optimized variable. Two optimization processes were performed by varying the weighting values on the cost function to determine the contributions of the assembly sequence and path planning objectively. The weighting values on the first optimization process were set to w_1 = 0.5, w_2 = 0.5, and w_3 = 0 to implement pure sequence optimization. This optimization process only utilizes the numbers of gripper exchange and assembly orientation change to find the best sequence for the assembly process. The weighting values on the second optimization process were set to w_1 = 0.25, w_2 = 0.25, and w_3 = 0.5 to consider both the sequence and path planning. The results of these optimization processes are shown in Table 1. For the first optimization, the number of orientation changes, O, is 0 and the number of gripper exchanges, G, was 2, which resulted in the sequence [6, 5, 3, 4, 2, 1]. On the other hand, since the second optimization result used the path information (repulsive force radius, ρ_0), O and G both increased to 3.

TABLE I
OPTIMAL ASSEMBLY ALGORITHM RESULT

A. $W_1 = 0.5$, $W_2 = 0.5$, $W_3 = 0$ (pure sequence optimization)

Sequence	Orientation	O	Grippers	G
6,5,3,4,2,1	4,4,4,4,4,4	0	G2,G3,G3,G3,G1,G1	2

B. $W_1 = 0.25$, $W_2 = 0.25$, $W_3 = 0.5$

Sequence	Orientation	O	Grippers	G
1,2,3,5,6,4	4,1,1,1,2,3	3	G1,G1,G3,G3,G2,G3	3

Sequence	ρ_0
1,2,3,5,6,4	3.69,3.41,4.03,4.41,3.69,3.64

TABLE II
GRIPPER TABLE

Part	P1	P2
1	G1	G2
2	G1	G2
3	G3	
4	G3	
5	G3	G4
6	G2	

The optimization only considered four principal axes for assembly orientation (x+,y+,x-,y-) which are represented as integer (1,2,3,4). Gripper options for assembled part in Fig. 2.B were provided by Table 2. For the second optimization process (Table 1.B), the result of optimized repulsive radius value was used to develop haptic guidance path (Fig.3) by using potential field method [16]. The quantitative effects of two optimal solutions will be explained in the user-studies section (Section 4) with real-time virtual assembly simulations.

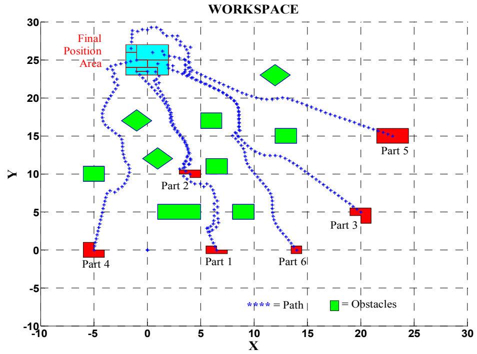


Fig. 3. A path planning optimization result using the second optimization scheme. The path will be used as haptic guidance path.

IV. USER STUDIES FOR ASSEMBLY TASK BY USING ENHANCED ASSEMBLY SIMULATION SYSTEM

An experiment was designed to evaluate the effectiveness of the enhanced haptic assembly simulation system with haptic path and sequence guidance from the suggested optimal assembly results. The process of moving parts from initial to final positions was the basic A/D task to be performed by the assembly operators participating in the experiment. Simulation schemes were prepared in three modes to evaluate the A/D task with the assistance of sequence and path planning (haptic guidance). The modes were classified as unguided (*U*), sequence-guidance (*SG*), and haptic sequence- guidance (*HSG*). When experimenting for each participant, the order of modes was chosen as a *U-SG-HSG* so that the users experience some help features. The operators followed four main assembly steps in each mode: 1) choosing a part, 2) choosing a gripper, 3) selecting the part, and 4) assembling the part. When performing the A/D task, the operator used certain assistance features, such as the optimized sequence of parts with guidance for gripper selection and assembly orientation, and the optimized assembly path. The availability of the help features depended on the selected modes

A. Modes for User Studies

1) Unguidance (U) mode: In this mode (Fig. 2.A), the operator selects and moves the parts one-by-one to their final positions without any guidance information (i.e., no help features). All parts appear in the workspace simultaneously. To select a part, the operator is required to choose an appropriate gripper from the available selection. Once the user selects a gripper, the constraints of the optimization process follow. Based on the selected sequence, the user does not need to make a gripper selection if the current gripper can handle the next part. Finally, the possible orientation directions will appear to a user as multiple arrow indicators for satisfying feasible assembly between parts. In this mode, the assembly path and orientation are fully under the operator's control without any assistance from the help features. The snapping-into-place mechanism when a part reaches its final position is the only extra feature available.

2) Sequence-guidance (SG) mode: In this mode (Fig. 4), the optimized sequence and guidance for gripper selection and assembly orientation are provided to the operator as help features. The results of the first optimization process (Table 1.A) are used in this mode as help features. The operator simply selects the parts and performs the assembly tasks based on the results of the optimal assembly sequence in Table 1.A. The suggested assembly sequence affects the order of each part's appearance in the VE as well as the gripper suggestion. After a part appears in the VE, the operator should choose a gripper. In this mode, the operator does have to use the recommended gripper to increase the possibility of using the same gripper for several parts that we had identified in advance. In this mode, the optimal orientation is also suggested during the assembly operation by an arrow-shaped indicator as shown in Fig. 4. The operator can assemble the part by orienting it as indicated by the arrow-shaped indicator. The assembly sequence is implemented such that only one part appears to a user for each assembly task. After the assembly of one part is complete, another part will appear in its initial position. This happens repeatedly until the assembly of all parts is complete.

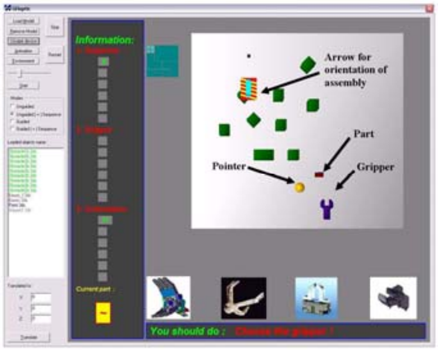


Fig. 4. Sequence-guidance mode

3) Haptic sequence-guidance (HSG) mode: In this mode (Fig. 5), the help features (optimized sequence of parts, gripper suggestion, and assembly orientation) are similar to those of the *SG* mode, with the addition of the optimal assembly path. The results of the second optimization process in Table 1.B are used in this mode. Similar to the *SG* mode, parts appear one at a time in the VE based on the optimal sequence, and are accompanied by the suggested path. For each part, the operator chooses the suggested gripper by touching it. During part assembly operation, the operator follows the path to assemble a part, orienting it as shown by the arrow-shaped indicator. After finishing assembling one part, the operator uses the optimal path to return to an initial position for the next part. The path is constructed in the form of a solid-body object in the VE based on the result of the optimal assembly algorithm. Movement is limited to the path boundary. Whenever movement begins to cross the path boundary, the operator feels haptic reaction forces between the pointer and the path boundaries. This haptic reaction feedback is expected to direct the operator's movements to the optimal assembly path. This scheme for passive haptic guidance with the optimized path planning results is considered as the optimized haptic path.

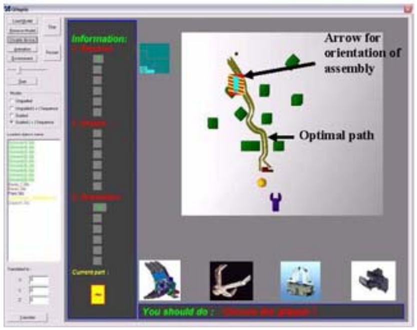
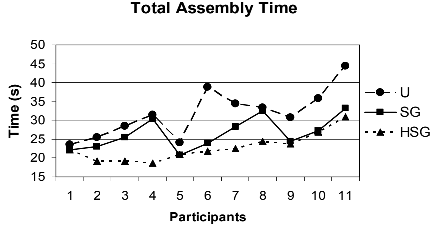


Fig. 5. Haptic sequence-guidance mode

B. Assembly Evaluation Parameters

Based on the assembly optimization schemes, we measured the assembly time and travel distance as final outputs of the haptic assembly simulation of the participants. The participants included 7 men and 4 women, aged 25–29 years. The assigned task (assembly case) was a planar assembly of the objects shown in Fig. 2.B. Each participant performed the assembly task in the three modes. The total assembly time and total distance traveled were measured for each participant during the virtual assembly operations. The total assembly time was the time to finish the assembly tasks of all parts, including gripper selection and part transition. The total travel distance was the overall distance traveled by the user from the initial to the final positions for all the parts, including any additional movements for gripper selection and parts transition. A short total assembly time and small total travel distance are desirable for effective assembly. Each participant was allowed to try the system several times to become familiar with the haptic device and some virtual environment components.


Total Assembly Time

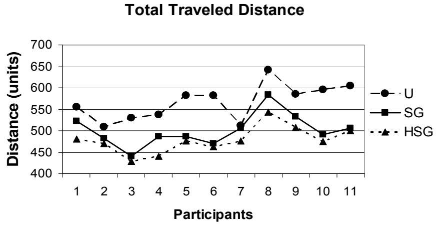

Total Traveled Distance

Fig. 6. Evaluation results for each participant. The data were taken from user studies of 7 men and 4 women, aged 25–29 years.

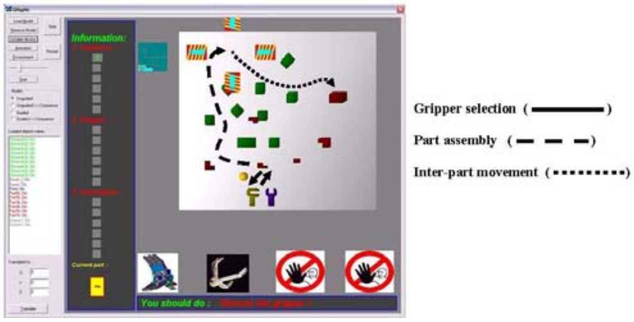


Fig. 7. Assembly sub-task. Classification of assembly into its sub-task was intended to analyze the performance improvement.

TABLE III
USER STUDIES RESULT

A. Overall performance of participants

Items	Mode					
	U		SG		HSG	
	T	D	T	D	T	D
Total	31.87	566.79	26.48	500.68	22.77	478.17
Std. Dev.	6.41	41.56	4.17	37.28	3.67	31.28
Improvement (%)	-	-	16.91	11.66	28.56	15.64
Gripper	3		2		3	
Orientation	3		0		3	
Avg. Vel.	17.78		18.91		21	

B. Performance analysis for each assembly sub-task

Sub-task	Mode					
	U		SG		HSG	
	T	D	T	D	T	D
Gripper	6.79	129.35	4.50	94.62	5.46	114.17
Inter-part	9.83	193.00	9.22	193.23	8.56	182.11
Assembly	15.26	244.45	12.76	212.84	8.75	181.89
Total	**31.87**	**566.79**	**26.48**	**500.68**	**22.77**	**478.17**

* Improvement is shown compared to nominal value (U); T = time (s), D = distance (units)

V. RESULT AND EVALUATION

A. Evaluation of Overall System Performance

Fig. 6 shows that the performance of each participant depended on the mode. The results in Table 3.A are the average values for all participants. We used the *U* mode results as the base value against which to compare the others. Compared to the *U* mode, the time to finish the 6 assembly tasks was reduced by 16.91% for the *SG* mode and 28.56% for the *HSG* mode. The average distance traveled was reduced by 11.66% for the *SG* mode and 15.64% for the *HSG* mode. In addition, standard deviations were reduced as the mode progressed from *U* to *SG* to *HSG*, which means that the performance results of participants in the *HSG* and *SG* modes were more uniform than in the *U* mode. In the *U* mode, since the participants were likely to choose a non-optimal sequence and a non-optimal path, the numbers of gripper exchanges and orientation changes were larger than in the *SG* mode, and the assembly time and the distance traveled were longer than in the *HSG* mode. In the *HSG* mode, the participants tended to use a higher velocity for the assembly task due to the optimized haptic path and the pre-determined sequence. This can be observed in the comparison of average velocities, as shown in the last row of Table 3.A.

To illustrate the differences of the contributing components in the three modes (*U, SG,* and *HSG*) clearly, we divided the assembly task into three sub-tasks: gripper selection, inter-part movement, and part assembly. Figure 7 shows the sub-tasks in the virtual assembly simulation, and Table 3.B summarizes the average operator performance for each.

Table 3.B shows that for gripper selection, the *SG* mode gave better results than the *HSG* and *U* modes in terms of time and distance since it had fewer gripper exchanges. Note that the operators using the *HSG* and *U* modes had to make one more gripper exchange, requiring more time and distance. Therefore in the gripper sub-task, the differences (21.3% for time and 20.6% for distance) between the *SG* and the *HSG* modes represented the effect of one more gripper selection. However, even though the number of gripper exchange was equal for the *U* and the *HSG* modes, the performances of the *HSG* mode were slightly better in the *U* mode since the gripper selection of the *HSG* mode was automatically supported by the helping feature. The effect of the gripper selection guidance on the overall assembly process is clear from the results of this sub-task.

The inter-part movements section of Table 3.B shows that the *HSG* mode was better than the other two modes in this sub-task. This was because in the *HSG* mode, the optimized path, which was shown for the next corresponding part, could be used as the haptic path guidance to reach the initial position for the next part. In the *SG* and *U* modes, the results for the inter-part path sub-task were not significantly different since the paths were fully under the control of the operator. The effect of haptic path guidance on the overall assembly process is clear from the results of this sub-task.

In the assembly sub-task, the *HSG* mode gave the best results in terms of time and distance. This was due to the optimization process that included path planning. The optimal path planning with the desired assembly direction minimized the necessary distance and time during the assembly task. The *SG* mode was better than the *U* mode since it used the optimized orientation information in the form of the arrow-shaped indicator.

Therefore for the assembly sub-task, the differences between the *HSG* and the *SG* modes (31.4% for time and 14.5% for distance) represented the effects of the optimized haptic path, while the differences between the *SG* and the *U* modes (16.4% for time and 12.9% for distance) represented the effects orientation guidance help feature. In this case, the *U* mode had three more orientation changes than the *SG* mode, as shown in Table 3.A.

Overall, the *HSG* mode had the best virtual assembly results in terms of time and distance. The detailed analyses of the assembly sub-tasks show that the performance improvements were mainly due to the reduced travel distance during parts assembly and inter-part movements with the haptic path guidance. Also, compared to the *U* mode, the *SG* mode had better results due to the optimal sequence with the gripper and orientation guidance. Thus, the optimized helping features improved the effectiveness of the assembly task during simulation.

VI. DISCUSSIONS

In all modes, the grippers are located at some fixed distance from each part's initial position. This scheme was chosen since the optimization process does not consider the gripper's position. In this way, the effects of the number of gripper changes can be clearly investigated. In addition, to avoid the tendency to choose only the part nearest the initial HIP location, the initial HIP position is selected randomly in each trial from among the 5 possible positions shown in Fig. 2.A.

Several haptic features have been considered for effective use of the optimized haptic path. The influences of the operator's movement in the *Z*+ direction should be minimized in evaluating the assembly task for planar assembly. By adding an invisible object parallel to the floor, the pointer can only move in the space between the floor and that invisible object (Fig. 2). The cross-sectional shape of the path boundary is also taken into consideration. In the suggested 2D assembly haptic interaction, the wall-type (rectangular) shape provides a better haptic sensation than the semi-circular shape. Finally, the width of the path boundary can affect the performance of the operator following that path. Wide path boundaries provide more freedom to the operator, but the operator movements are not uniform. On the other hand, when the path boundary is too narrow, the HIP is difficult to move. Thus, we carefully selected the width of the path boundary to keep it sufficiently small while still allowing free operator movement. With careful haptic path designs, the operator can move freely inside the path without problems such as binding or sticking. The repetition of virtual assembly tasks by the haptic feedback is expected similar to the effect of real repetitive training.

VII. CONCLUSIONS

We have described an enhanced haptic assembly simulation system with an optimized haptic path and sequence. The system included an optimal algorithm to enhance the effectiveness of the assembly task. The proposed haptic assembly simulation system allowed an operator to achieve the optimal assembly process by following an optimal assembly sequence and optimal haptic paths. The experimental results showed that compared to the unguided mode, the *HSG* mode was 28.56% better for assembly time and 15.64% for travel distance, while the *SG* mode was 16.91% better for assembly time and 11.66% for travel distance. The detailed analyses of each assembly mode showed that for the *HSG* mode, the performance improvements were mainly due to the reduced travel distance during parts assembly and inter-part movements, while for the SG mode, mainly due to the reduced numbers of gripper exchanges and orientation change. We can conclude that the optimized haptic path, as well as sequence guidance, enhances the working performance of virtual assembly tasks. In addition, the developed haptic assembly simulation system can be a framework to verify the effectiveness of optimal assembly algorithms. In future work, the virtual assembly system and the assembly algorithm will be extended to a more complex simulation scheme with 3D mechanical parts to apply the proposed virtual assembly scheme to more practical applications, such as aircraft parts assembly.

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