DEVELOPING A VIRTUAL ENVIRONMENT FOR AIDING ASSESSMENT AND IMPROVEMENT OF ASSEMBLABILITY OF AEROSPACE STRUCTURES

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The goals are to support assembly planning; simulation; and evaluation, primarily for manual assembly. The objectives are: automated/computer assisted planning of alternative assembly sequences; development of a virtual platform for realistic assembly simulation; and development of metrics for automated evaluation of ergonomic assembly difficulty. The major challenges and key results obtained so far are reported.

Keywords: Assembly difficulty, Sequence planning, Virtual reality, Haptics.

1. GOALS AND OBJECTIVES

The overall goals are to support assembly planning; simulation; and evaluation, primarily for manual assembly. The objectives, respectively to fulfil these goals, are: automated or computer assisted planning of alternative assembly sequences (Section 2); development of a virtual platform for realistic assembly simulation (Section 3); and development of metrics for automated evaluation of ergonomic assembly difficulty (Section 4).

2. PLANNING OF ALTERNATIVE ASSEMBLY SEQUENCES

Assembly sequence planning is to determine the sequence in which the parts are added to form an assembly. Disassembling is a process in which the parts are removed from a given assembly typically, in a reverse sequence. A survey of research in disassembly sequence generation is given in [1]. In this work, we disassemble an input assembly to get an assembly plan. At any stage of assembly, there could be multiple candidate parts that could be added independently leading to multiple assembly sequences. Typically, the number of feasible sequences grows exponentially with the number of parts in an assembly. The major factors affecting an assembly plan are geometric feasibility (no interference among parts during assembly), ergonomic suitability and infrastructure availability (tools, fixtures, parts, sub-assemblies, machines and humans). In this work, we consider only geometric feasibility of assembly plans.

A part is removed from an assembly by combination of single or multi-step translations and rotations. We consider only single step infinite translation along a direction. A part in free space can translate

Research into Design — Supporting Sustainable Product Development. *Edited by* Amaresh Chakrabarti
 :: *Published by* Research Publishing
ISBN: 978-981-08-7721-7

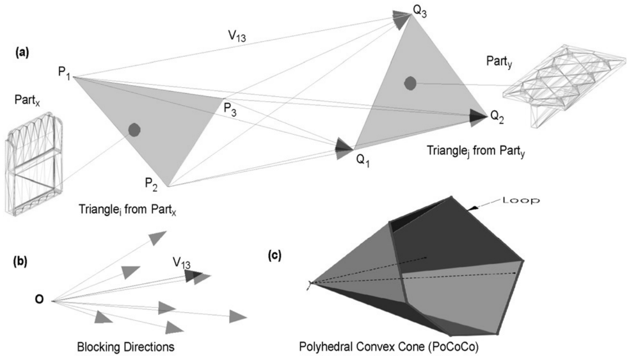

Figure 1. Computation of PoCoCo for a triangle pair.

in all directions represented by a unit sphere. A part in an assembly is restricted to translate in certain directions due to collision with other parts. These directions are blocked directions and are grouped into blocked regions. The region containing directions for obstruction free removal of a part is free region. We identify a blocked region/s for each pair of parts in an assembly; combine all the blocked regions for pairs of a part with all remaining parts; and look for any free direction/s available for that part to be removed from assembly. The methods for computing, representing and manipulating these directions are outlined in the next section.

2.1. Computation of Blocked Directions

The input for our application is a set of tessellated parts in assembled configuration. A set of blocking directions between two parts is determined by combining the sets of blocking directions for all triangle pairs between them. The non-contacting and mutually invisible triangle pairs are discarded. The blocking directions for a pair of triangles are computed as shown in Figure 1. An i^{th} triangle from x^{th} part and a j^{th} triangle from y^{th} part are shown in Figure 1 (a) that are mutually visible. The vertices of the triangles are marked as P_i and Q_i respectively. A vector is drawn from every P_i to every Q_i. All these nine vectors are moved to the origin as shown in Figure 1 (b). A minimal polyhedral convex cone (PoCoCo), containing all these directions, is shown in Figure 1(c) in a different view. Each facet of a PoCoCo is a triangle formed by the origin and two endpoints of the supporting vectors. PoCoCo is represented as a loop that is an ordered sequence of 3D points.

2.2. Representation and Boolean of directions

Instead of unit sphere, a unit cube-grid [2] is used to represent the directions. Each loop is projected on a unit cube and the face-grid is computed. Boolean of blocked regions is computed as shown in Figure 2. Green cells represent the free directions and the blue cells represent the blocked directions. The red cells are on the boundary between these two regions and contain the directed edges of the loops. Each edge in the red cell divides it into green and blue region. Depending on how the multiple edges in red cell interact, we get a green region, a line segment or a single point representing the free direction/s in the red cell. The cube-grid representation reduces the computation for combining the regions without sacrificing the accuracy. When all the cube grids for all the loops are combined, we get the cube-grid for that part pair. We used a test box assembly shown in Figure 3 provided by Boeing Company for demonstration. The test box assembly has 15 parts that gives 105 distinct part pairs. The cube-grids for some part pairs are shown in Figure 3(c). The cube-grid for a part pair is stored into a grid file and an edge file. Grid file contains 6 matrices of (grid size × grid size) for 6 faces of the cube. Each element in these matrices is the colour of the cell at that position. The edge file contains the set

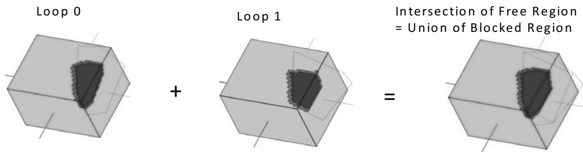

Figure 2. Boolean of PoCoCos on cube-grid.

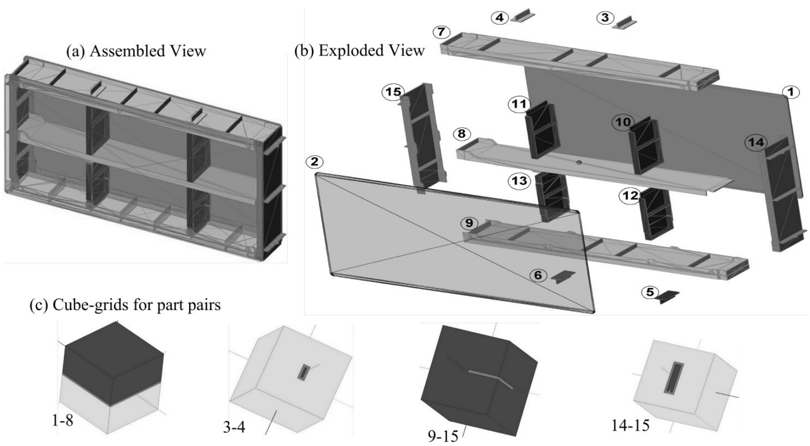

Figure 3. Boeing test box assembly.

of edges present in the red cells. The cube-grids are combined by combining the corresponding cells on corresponding faces by applying the rules given below in that order.

1. If any of the cells is blocked (blue) then the resultant cell is blocked.
2. If boundary cell/s (red) are present then resultant cell is boundary cell and the edges from all boundary cells are accumulated.
3. If all cells are free (green) then the resultant cell is free.

2.3. Interactive Assembly Planner

In the absence of a practical computer-aided assembly planner for large assemblies, an expert plans an assembly based on his experience and the knowledge about a particular assembly, production facility and other resources contributing to the assembly process. For an established product, the variants and new versions differ only in few components and placements. The computational effort required to find all the assembly sequences, to filter feasible sequences and to choose an optimum sequence for a small change in assembly is not justified. An assembly planner is interested in knowing whether an old assembly sequence is still valid for new parts and placements. If not at what step it is invalid and because of which part. We provide an interactive assembly sequence validation and planning tool that checks for the geometric feasibility of an assembly sequence at each stage. Since the computations required in this scenario are minimal compared to finding all sequences, the tool interacts in real time.

Assembly Sequence Validation and Planning Tool: For a given assembly sequence, this tool checks if it is a geometrically valid sequence. It starts with the first pair of parts in assembled configuration and adds the next part in sequence at each successive step. It finds the free directions for the newly added part with respect to all the parts added before it. If a part could not be added at a particular step then the tool reports the given sequence as invalid along with that part id. In sequence planning mode, the user interactively adds or removes the parts and tool validates the sequence at each step as described before.

3. VIRTUAL PLATFORM FOR ASSEMBLY SIMULATION

The present work is towards assessing the difficulties of large flexible structures in virtual environment. To simulate the assembly situation in virtual environment we need high precision and fidelity of the hardware and software. The user should be able to manipulate the parts in the virtual space to construct an assembly with realistic assembly operations. A realistic virtual environment should be able to capture the diversity of assembly scenarios involving the visual capabilities, skill and manipulating capabilities of the operator. It should reflect all types of assembly operations and all kinds of fits.

3.1. Challenges

The challenges in this implementation are listed below.

Realistic modelling of the assembly activity: Realism in a virtual environment should be achieved through visual as well as haptic feedback. Assembly modelling based on the configuration space is unrealistic and inefficient with respect to memory and time [3]. Assembly modelling based on geometric constraints [4] like axis alignment, vertex coincidence is non-intuitive. Hence, the simulation experience is likely to be unrealistic and the real difficulties of assembling may not be revealed.

Determination of forces: The forces and torques, acting in an assembly activity, are complex. The interaction of hand-part and part-part are to be modelled. The simpler of the two, part-part, is quite difficult to solve as it requires complex rigid body dynamic interaction that is time and memory expensive. We need to come up with a novel force determination technique for hand-part as well as part-part interaction. To render these forces, we require high haptic refresh rates.

Overcoming the Limitations of haptic devices: The force rendering devices hinder realism in terms of both the amount and the types of forces that can be rendered. Torque cannot be emulated with the available devices using the force feedback. We worked with two devices PHANTOM® omni and CyberForce together with CyberGrasp. PHANTOM® omni is a point based force feedback device that can exert maximum force of 2.65N at nominal position. CyberForce is a force feedback armature that conveys forces to the hand in three dimensions with a maximum positional force of 8.8 N. CyberGrasp which is a force reflecting exo-skeleton allows a maximum continuous resistive force of 12N per finger. Since this force is more like a pull, frictional forces that are normal to the fingers cannot be emulated. The challenge here is to provide realistic force feedbacks to the user within the possible ranges.

Simulating tolerances in virtual reality: The virtual environments should reflect realistic part tolerances. Current literature suggests that the clearance between the parts in virtual environment is high [5]. For simulating tight tolerances, with collision detection schemes based on interference detection, the micro level movements between the parts cannot be determined with precision. The challenge, hence, is to include tight tolerances without affecting the user performance.

Integration of devices: Creating a realistic assembly environment in virtual world requires facilities for realistic display and haptic feedback. Various devices like force feedback devices, trackers, head mounted displays for stereo vision are required to be enabled simultaneously. It is a challenge to make these systems work simultaneously as they have different Application Programming Interfaces, different libraries, and more importantly the underlying assumptions are different. Other challenges in achieving the required results include speed and accuracy in computing and rendering the forces.

3.2. Resolving the challenges

Proximity Detection: Proximity detection is done by monitoring distance between two parts based on the closest points. A well-established method in literature, for determining the minimum distance between convex objects is the iterative Gilbert-John and Keerthi distance algorithm [6]. The accuracy is higher than that of the collision detection based methods as the computation happens before the interference takes place. Proximity detection can also be used to capture the design intent of the assembler.

Feature based schemes for detecting kinematic pairs in an assembly: An assembly action, as in case of a peg and hole, can be broken down into two phases: alignment and insertion. During an alignment operation, accuracy is not critical. Hence, collision detection can be used for force rendering. When physically assembling, force based part- part interaction helps in self alignment. The cues obtained during to this guiding process can be emulated using deviation from the ideal as a metric. Force feedback can be given such that the user is guided to move in the direction of the allowed motion.

With various steps of assembly, the number of degrees of freedom for a part reduces due to its contact with other parts, and a kinematic pair is formed between them. Identifying compatibility from a kinematic point of view will help us carry out the actual task of insertion. The intent of the user can be captured by identifying a local region of interest, based on the kinematic pair to be formed in the assembly.

Addressing various types of fits: To simulate various assembly conditions within the insertion process, the three kinds of fits have to be considered. The force feedback in these cases will be different. For instance, in a vertical arrangement, in clearance fit, once the alignment takes place, the assembler need not give any extra force to complete the assembly. The gravity helps the insertion process. In transition fit, after the alignment, a constant force is required to finish the insertion. For interference fit, an increasing amount of force is required to finish insertion, once the axes are aligned.

Rendering forces and graphics: Motion applied to a part can be divided into two components. The motion of the virtual part in the direction of allowed motion causes motion that can be rendered as graphics. However, any motion perpendicular to this will not contribute to the motion and can be rendered as the forces to the hand. The motion of a part and the previous state is critical for determining the collision response vector. As shown in the Figure 4, the current state of the system is not sufficient. The direction in which the user feels a force feedback is dependent on the direction of the motion.

Rendering frictional forces: As discussed earlier, the frictional forces cannot be rendered with the current force feedback devices. Without these, assembly difficulties due to slipping due to friction cannot be reflected. Since these forces cannot be given as a force feedback along the fingers; it can be shown in graphics to depict slipping motion.

3.3. Discussion

To establish the extent of realism that can be achieved, using PHANTOM® omni, an assembly environment for 'Towers of Hanoi' was developed as can be seen in Figure 5.

In this problem, the user has to stack the discs in the order of their size, by moving from one rod to another, following certain rules.

The idea is based on Kinematic modelling of assembly for tessellated objects [7] that enables the user o assemble two parts represented in tessellated format. The necessary geometric features (surfaces)

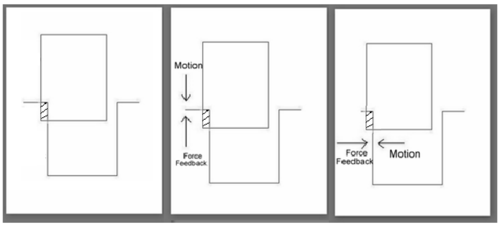

Figure 4. Different directions of force feedback for different directions of motion.

Figure 5. Towers of Hanoi suing PHANTOM.

from STL part models are identified through segmentation, curvature analysis and surface normals. This kinematic assembly modelling structure has been extended to accommodate more number of parts to build the environment for 'Towers of Hanoi.' The scheme followed is to find out the minimum distance between two parts. When parts are close enough, the points in the proximity are identified. This is captured as a "region of interest". A set of triangles for joint identification are isolated which are in the "region of interest". This results in the decrease of time for computation. Another application, AutoKAM [8] is used to identify the joints. Finally, the allowable direction of motion and ranges of motion are calculated. The deviations from the allowable directions of motion in orthogonal space are used for rendering the forces and motion. Interfacing of different devices and also the exact amount of force to be given as a feedback to the user are in the process of development.

4. EVALUATION OF ASSEMBLY DIFFICULTY

4.1. Overview

This section discusses the techniques being developed for assessment of assembly difficulty. These techniques will be incorporated in the virtual environment for evaluation of assembly difficulty of aerospace structures. Experiments on manual assembly of computer frame were analysed to develop techniques based on time and postural analyses to assess difficulty. This combined analysis technique is discussed in this part and the other challenges which need to be solved are identified at the end of this section.

The overall objective of this part of work is that given a manual assembly scenario, which can be performed either in real or virtual environment, how to evaluate the assembly difficulty automatically. Earlier, we proposed a manual evaluation process that combines time and postural data [9]. Since the manual process takes a long time and can have less accuracy, we intend to convert this into an automated process using electromagnetic tracking systems used in virtual reality. The difficulty in each assembly task is planned to be evaluated using our earlier proposed method which uses both time and postural data [9]. The difficulty so assessed, for each assembly operation, will then be mapped to measurable difficulties such as those with visibility and reach. These can be measured in terms of a change of body angles. For example, Reach can be measured as a change in angle of torso. These measurable difficulties will then be associated with controllable parameters responsible for causing the difficulties. We propose that these parameters are grouped under five major categories: part, person, process, tool and environment. By controlling these parameters, the root causes of difficulty could be eliminated or reduced.

4.2. Challenges

The various challenges to be addressed to establish our idea of automatically generating evaluation process of assembly difficulty are: how to measure difficulty of individual assembly operations and integrate these into overall difficulty of a set of assembly operations; how to map these into measurable difficulties in visibility, access and force application; how to map these to controllable parameters in part, person, product, process and environment; how to automate computation of the assembly evaluation process.

In this work we focus on the first of the above challenges. Traditionally, assemblability is assessed by Design for assembly (DFA) methodologies [10, 11]. These approaches do not take into account about the influence of ergonomic elements of the humans who assemble the parts within a product. In assessing manual assemblies, it is essential to take into account human involvement and the problems faced by human operators. Literature review indicates that manual assemblies are assessed primarily by two methods: Ergonomic postural analysis and predetermined time systems. For ergonomic postural analysis, generally two methods have been used (observation based techniques and instrumentation based techniques) to record the postures that a human operator maintains during assembly. In observation based techniques, video recording is used for postural analysis [12, 13]. In instrumentation based techniques, devices are attached to a person for the measurement of characteristics of a specific body segment [14]. These category of work focuses mainly on ergonomics of human who is performing assembly. The assembly process or the source of difficulty is not considered.

The other techniques for assessing manual assemblies are based on predetermined time systems [15, 16]. All the above discussed methods were interested in finding the difficulty at the operation level. Finding the source of difficulty or resolving the difficulty was not addressed.

Interestingly, Desai and Mital [17] evaluated disassembly operations using an analysis that is based on a time scale that combines an ergonomic approach, i.e. a penalty is given for poor postures while calculating difficulty based on a time scale. They list some of the attributes responsible for difficulty and give suggestions to alter the design in terms of geometry of the part. The changes that can be made in other areas such as process or environment were not discussed. In terms of automation of assessment of assembly difficulty, little is reported except for a semi-automatic process based on time to determine ergonomically hazardous work elements [18]. Our research objective is to develop an approach for automated assessment of assembly using a combination of postural and temporal measurements that are both captured and analysed automatically. Analysis of the measured data is to map the difficulty to its source in terms of part, process, person, tool and environment.

4.3. Research Approach

The first step in the research approach was to video-record an assembly process of computer frame assembly carried out in a laboratory setting. Ten male subjects with mean age of 29.2 years, height 168.5 cm and weight 66.5 participated in carrying out the assembly. The video was transferred to the computer for analysis. The video was edited and viewed by the researcher, in order to define the tasks, operations and frames involved in the assembly. The assembly was decomposed into 6 basic operations [16]. The assembly of computer frame is divided into six operations as listed below; a snapshot from each operation is shown in Figure 6: a) Fixing the left panel, b) Fixing the top left screw, c) Fixing the bottom left screw, d) Fixing the right frame, e) Fixing the top right screw and f) Fixing the bottom right screw. Each operation has multiple tasks (say for example move, align, etc.,) within it. The video is then used by five evaluators (including the assemblers) who assessed each task, and the researcher. The evaluator rated the difficulty of each operation involved in the assembly. The researcher analysed the data to rate postural and time related data.

(a) (b) (c) (d) (e) (f)

Figure 6. Various operations involved in computer frame assembly (a-f).

Table 1. Various relations and their calculated correlation coefficients at operation level.

S. No.	Relations	Correlation Coefficients
1	Feedback (FB) Vs RULA_Right(Rr)	0.162
2	FB Vs Rr*RULA_left (Rl)	0.171
3	FB Vs Rl	0.209
4	FB Vs Time(T)	0.348
5	FB Vs Rr*Rl*T	0.365

4.4. Results to resolve the challenges

4.4.1. Combined postural and time related data for assessment of assembly

The list of outputs of the postural data (RULA analysis) and time analysis are compared with the average feedback obtained from the evaluators at the operation level. We argue that the strength of correlation with average evaluator feedback is the most appropriate validation in the absence of any other formal criterion available. We, therefore, correlated the postural and temporal metrics individually and combined with the average evaluator feedback at operation level, as shown in Table 1. The null hypothesis used was that "there is no correlation between the metric under consideration and the evaluator feedback" and is checked using Spearman's rank correlation at 99.9% confidence interval. The accepted value is 0.303 for $n = 60$ and $p = 0.01$. The result shows that the calculated values in the first three cases lie within the acceptable region. So, we accept the null hypothesis for the first three relations, and reject for fourth and fifth cases. We therefore conclude that there exists a significant relation between the metrics under consideration in the fourth and fifth cases, with the fifth case being the most highly correlated.

4.4.2. What remain to be resolved

The work remaining involves identifying the sources and root causes of difficulty that are responsible for the assessed difficulty in assembly. The unresolved challenges are: how to map time and postural data these into measurable difficulties in visibility, access and adjustment; how to map these part, person, tool, process and environment related parameters; and how to automatically compute the assessment process of assemblability.

5. OVERALL SUMMARY, CONCLUSIONS AND FUTURE WORK

The paper reports three major outcomes: an approach for detecting overlap among objects and an assembly sequence planning approach that uses this; a realistic virtual simulation approach for tight tolerance assemblies that combines collision detection and kinematic-pair based analyses; and an approach that uses time and postural data for assessment of assembly difficulty. A host of challenges remain, and are part of our future work.

ACKNOWLEDGMENTS

We thank Vinayak for providing and helping us in modifying the cube-grid code. We thank the participants in the assembly exercise used in this work. We thank The Boeing Company, USA for providing the test box, and financial support under SID project 36011 of Indian Institute of Science, Bangalore, India.

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