Haptic Virtual Reality DFMA - A Case Study

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Abstract. Design for manufacture and assembly (DFMA) provides a key way of improving the design of products, however current tools for this type of analysis have not taken an integrated approach. This paper provides a brief review of the literature concerning DFMA and computer aided versions before presenting a new DFMA system virtual paradigm. This combines previous approaches to DFMA with the addition of a haptic virtual reality-enabled modelling and assembly environments to provide interactive feedback on the design as the assembly and individual parts are edited in an iterative process. The operation, functionality, and implementation of the system are described followed by a case study in mechanical engineering design illustrating the system's application. The paper concludes with a discussion of the case study results and conclusions on its success.

Keywords: Design for manufacture and assembly · DFMA
Design for assembly · DFA · Haptics

1 Introduction

The design of products is a major driver of the product lifecycle cost [1, 2]. Methods that assist designers to improve the design of products such as DFMA can have a substantial impact on this cost by considering the factors that cause increased cost in the manufacture and assembly stages concurrently with the design process. DFMA accomplishes this by creating simpler product structures which are less costly to manufacture and assemble [3].

This work follows on from and extends previous work [4] by the addition of a new overview, extended functionality in the modelling subsection, and validation by means of a case study example.

2 Literature Review

The most widely adopted of the DFA methods are those of Boothroyd and Dewhurst [5], alternate approaches to DFA analysis include those described by Lucas [6]. These techniques have formed the base on which many DFMA systems have been designed. As the completion of this type of analysis manually is a lengthy process [7] much research has been focused on the automation of this process. An overview of some of the main approaches follows.

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A core of the automated approach lies in the extraction of geometric properties from 3d models. This includes the extraction of data pertinent to manual assembly analysis [8, 9] and the more complex analysis needed for automatic assembly [9].

Another approach take is the addition of expert systems to assist the user in the initial design of the assembly and the redesign process. An example of this approach is taken by Mei and Robison [10] where an assembly sequence advisor assists the creation of the assembly sequence and a part count advisor to provide feedback on the necessity of each part in the design. An expert systems approach was also taken by Sanders et al. [11].

In order to facilitate the integrated analysis and redesign of an assembly the addition of integrated CAD systems were developed. These include the designer's Sandpit introduced in [12] using previous work on automatic symmetry detection [13], expert systems [10] and assembly sequence evaluation [14] and was later expanded to include analysis of manufacturability [15] and design complexity analysis [16].

All the above described CAD integrated systems make use of traditional parametric CAD interfaces. These provide sufficient functionality to create the desired model alterations, however it is time consuming and focuses on the detailed design of parts. An alternative interface approach to CAD is that of a sketch based interface which have been shown to quicker to learn, be more intuitive to use and allow for faster modelling times [17]. However, depending on the approach used these produce less precise models. For a more detailed analysis on different types of sketch based modelling see previous work [4]. This makes a good fit with the DFA process as it should be able to reduce the time needed for the redesign process and DFA analysis is more tolerant of less detailed models which has been the focus of a number of works including [18, 19]. The approach of combining the use of a sketch based CAD interface and a DFMA system has not been taken previously, this is the focus of this work.

> *"Can haptic virtual reality with sketch-based interactivity provide new methods for evaluating and automating DFA criteria while capturing associated DFA knowledge in a unique fashion?"*

3 System Overview

3.1 User Overview

The process the user takes when interacting with the system is depicted in Fig. 1.

The user is guided through a series of steps to first evaluate their design from a DFA perspective. This includes the real-time background evaluation of the individual parts from a handling and insertion perspectives (see Sect. 3.3) which is constantly displayed. During this process the user assembles the design in the virtual environment using a haptic device. This is preferable when combined with 3D interaction as it has been shown in previous work that this considerably enhances the usability of assembly planning systems [20, 21]. A human-in-the-loop is central to our approach. Instead of using, for example, a semi-automated assembly sequence advisor - which may invariably need correction by an expert user – the assembly sequence is defined by the user from scratch using haptic assembly. Therefore, once the concurrent DFA evaluation is complete the user receives the results of the analysis and advice on the areas

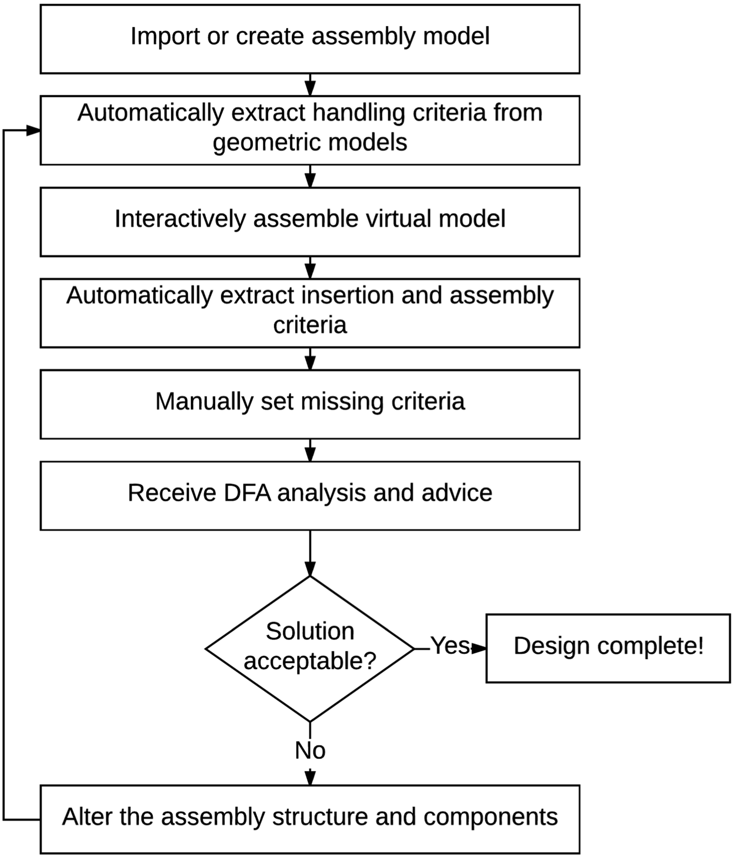

Fig. 1. User process flow diagram

that could be (further) improved. During each design iteration, the user can then make design improvements via the haptic geometric modelling environment, altering the design of the parts if required. Consequently, this concurrent DFA evaluation and geometry modification is substantially different from previous methods mentioned.

3.2 Technical Specifications

The system was developed using the Unity3d game engine. This allowed the physics interactions and graphical rendering and support for multiple input devices.

During runtime the models are stored using a boundary representation, this is achieved by the use of the Open Cascade libraries [22] (with the addition of a wrapper developed to integrate this with unity). In addition, this provides access to model import and export alongside extensive modelling tools.

Both the modeling and assembly subsections require the use of haptic feedback and 3d viewing to create an immersive experience. The haptic feedback is created using the Phantom Omni which using a stylus like device allows the user to experience the weight, surface texture and shape of objects. As this device is not supported by Unity the Open Haptics library [23] and a haptic plugin [24] are used.

The primary subsections of the system consist of an assembly overview where the user can see the assembly and receive feedback on the design and compare design changes; an assembly environment to capture the assembly sequence; and a modelling environment where the user can edit the geometry of the parts. These subsections are further described in Sect. 4.

3.3 Design for Assembly Overview

To evaluate the assembly the techniques described by Boothroyd et al. [25] are used. This analysis evaluates each of the parts in the assembly and any other additional operations needed such as reorientation or the use of power tools. For each of the parts three areas are evaluated: functional, handling, and insertion. Functional analysis covers the function of the part in the assembly and is used to determine whether the part is a suitable candidate for elimination. Handling covers the difficulties of picking up the part and orienting it correctly for addition to the assembly. Insertion covers the difficulties of inserting the part into the assembly. Both handling and insertion are evaluated into codes which correspond to times to complete the operation. For non-part addition operations Boothroyd and Dewhurst have included several additional codes corresponding to several types of common operations. Functionality is evaluated by a series of questions asked to the user evaluating to a 1 for a part that is essential in the assembly or a 0 for a non-essential part.

To complete assignment of the codes data must be collected for each of the parts (referred to as DFA criteria), an overview of the needed data can be seen in Table 1.

Table 1. DFA criteria for addition of parts

Functional	Handling	Insertion
Reason for being a separate part	Bounding box shape	Type of insertion
Function served in assembly	Bounding box size	Insertion difficulties
	Alpha symmetry	
	Beta symmetry	
	Handling requirements	
	Handling difficulties	

4 Subsection Description

4.1 Assembly Overview

In the assembly overview the assembly is displayed in the form of an assembly tree Fig. 2. This allows a high-level overview of all the components in the assembly at once. A previously modelled assembly can be imported at this point or a new assembly can be created with the tools provided. Once the assembly is constructed/ imported some DFA metrics can be captured automatically. Bounding box shape and size [9] main axes, symmetry, mass (to infer ease of handling). With the addition of noting any additional handling difficulties this is enough data to assign a handling code to each of the parts. All criteria can be set manually and automatically captured data can be overwritten.

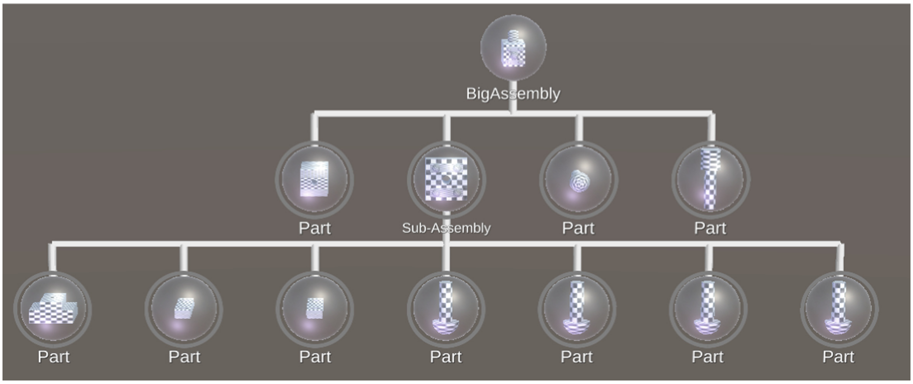

Fig. 2. Assembly tree

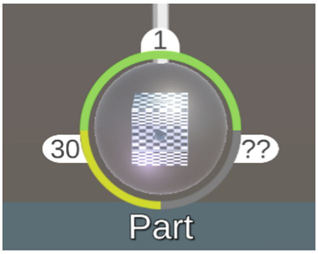

Fig. 3. Ring around part

Each component in the assembly has a ring surrounding its representation in the assembly tree, this ring is split into three sections representing the codes for functionality (top), handling (bottom left) and insertion (bottom right) respectively Fig. 3. Once enough information has been gathered to evaluate a section that section is assigned a color based on the time associated with that code Fig. 4 (or in the case of functionality green for a 1, red for a 0). The code can also be viewed by hovering over the part. This provides a high level view of the assembly components allowing for simple identification of problem parts at a glance.

Fig. 4. Segment colorings (Color figure online)

If the full evaluation is not complete the user is prompted to take the appropriate action to complete the data either manually or by being directed to the assembly sequence capture subsection.

4.2 Assembly Sequence Capture

This is used to capture the assembly sequence for the top level of the assembly or a subassembly. It is also used to capture insertion information associated with the addition of each constituent part.

The models comprising the selected assembly are loaded into the scene within reach of the haptic device. The user then can select the pieces one by one and put them into place in the final assembly. The user can also take actions to reorient the assembly or use one of the available tools to perform an additional operation e.g. the fastening of screws with a power drill. The actions of the user are captured and the resulting operations are displayed in a time line at the bottom of the screen Fig. 5.

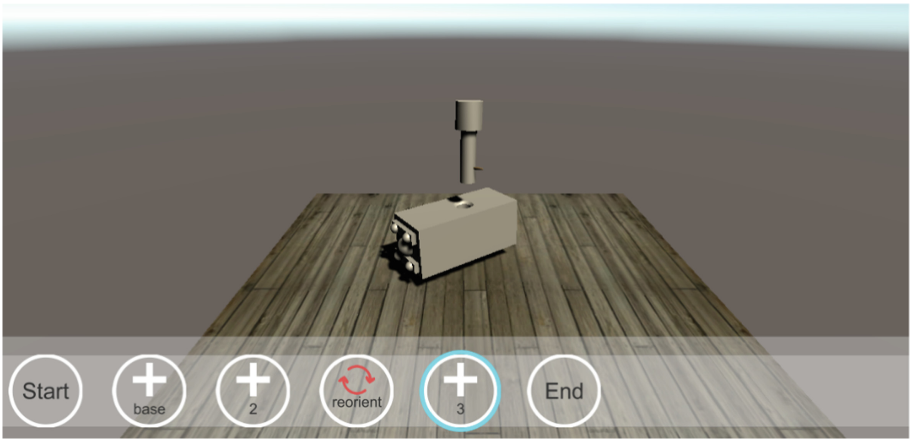

Fig. 5. Capturing the assembly timeline

From this process, a number of DFA metrics are extracted. The sequence of operations, any additional operations needed, difficulty of part insertion, assembly direction, and insertion axis. Once this is complete this provides enough data to evaluate an insertion code for each part and additional operation.

4.3 Processing DFA Metrics and Creating Feedback

Once all the parts and additional operations have been evaluated and given the appropriate codes suggestions for improvements are generated. There are three different categories of feedback: part combination/ elimination suggestions; handling improvements; and insertion improvements. These are displayed to the user in the form of circles displayed next to each part in the assembly hierarchy. These circles are located beside the ring section the type of advice contained corresponds to and can be expanded to display the details of the advice being offered Fig. 6.

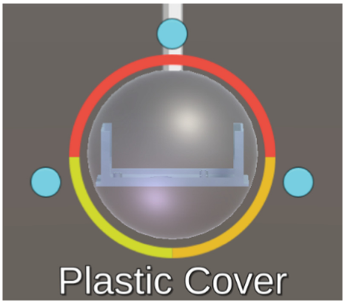

Fig. 6. Advice bubbles

Advice Generation

The advice is generated using a combination of the DFA metrics collected for each part and assembly operation and knowledge of the assembly structure. E.g. which parts are connected. The types of advice generated can be seen in Table 2.

Table 2. Advice types generated

Functional advice	Consider combining with part X*
	Consider combining with another part
	Consider combining part X and part Y
Handling advice	Consider making more symmetrical
	Redesign to make less prone to nest/tangle
	Redesign to eliminate need for grasping tool
	Redesign to eliminate need for careful handling
	Redesign to make less slippery
Insertion advice	Consider eliminating need to hold down
	Consider making easier to align or making self-aligning
	Redesign to make access to assembly location easier
	Redesign to make sight to assembly location clear
Assembly operation advice	Consider combining parts to eliminate need for screws or consider using snap fits
	Consider combining parts X and Y to eliminate need for screws or consider using snap fits
	Consider redesigning the assembly to be assembled without reorientation
	Consider eliminating the need for additional assembly operations

*Part X and part Y are the names of particular parts in the assembly.

In addition to the advice attached to individual parts a timeline of the assembly operations is shown with bar length corresponding to the time each operation takes to complete and the type of operation depicted underneath. Figure 7 (this is where the assembly operation advice is displayed).

Fig. 7. Timeline

A percentage score comparing this assembly with the ideal assembly is shown. Where the ideal assembly is one with only the minimal parts which needs no additional operations with each operation taking 3 s to complete.

4.4 Model Editing

For the redesign the parts a modelling environment is required. The modelling subsystem allows the user to edit the geometry of parts with the haptic device. During this modelling process the user receives feedback on effect of their design changes on the handling characteristics of the part.

The user has access to a number of different modelling operations as described in the following sections.

Sketch Creation
Sketches are created on planes of the model by using the haptic device to draw as with a pen on the surface. The path of the pen tip on the plane is captured and processed into one to five viable interpretations. These interpretations are then ranked and the highest scoring interpretation is displayed on the model and the next most likely interpretations are displayed in an array on the screen Fig. 8 where an alternate may be selected if desired.

Sketch Editing
Any sketch on the model can be edited. Sketches can be scaled, aligned with model features, e.g. an edge of a sketch with the edge of a face, rotated, and combined with other sketches on the same plane.

Add/ Remove Material
By using the stylus to select a closed sketch loop on a face and while holding the second button pull or push the profile in the desired direction (perpendicular to the face) to create an extrusion or cut into the part model. While the user is dragging the sketch a preview of the new geometry is displayed, if this creates a cut into the part some of the faces are switched to a transparent material to allow the user to see what they are doing. Snap points are created at heights where other planes perpendicular to the sketch plane are located. If a specific height for the extrusion is required this can be selected manually (Fig. 9).

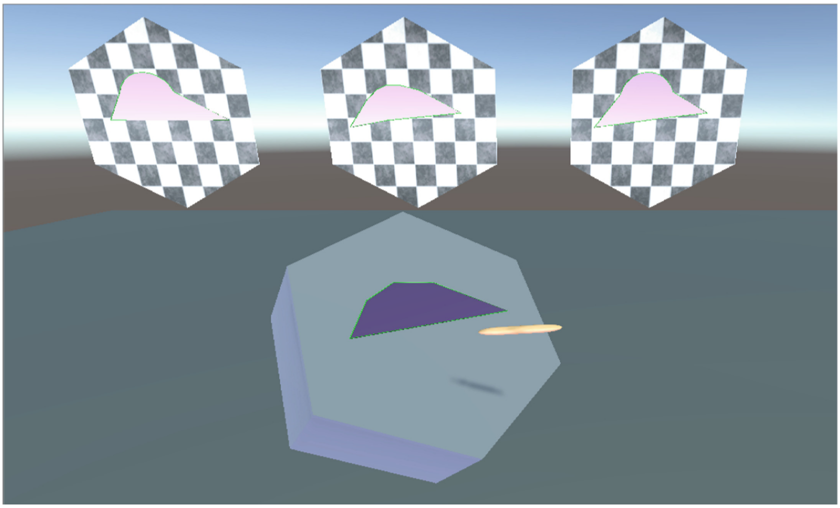

Fig. 8. Example of alternate sketch interpretations

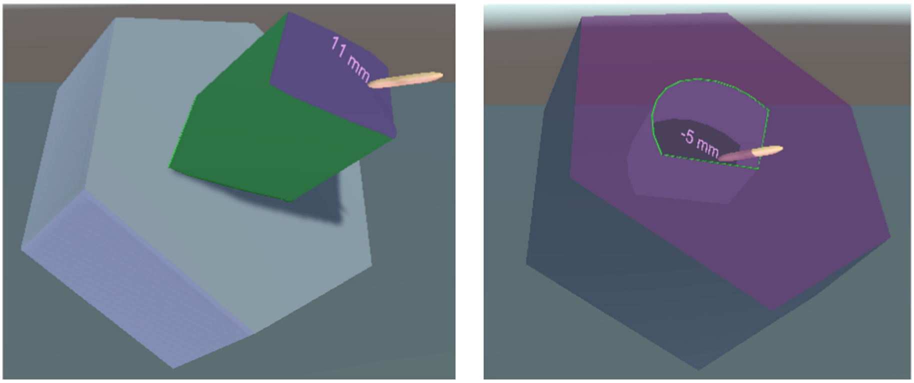

Fig. 9. Addition and removal of material from a sketch

Move Faces
Planar faces of the model can be moved in a similar fashion to the extrusion of sketches, allowing the user to simply edit the shape of the part (Fig. 10).

Delete Features
To delete a face or edge in the model the user selects the desired target with the stylus and initiates the delete command. This removes the selected feature from the underlying BRep model then recursively removes other edges and faces invalidated by the removal of the other faces and edges. The new model then replaces the original model.

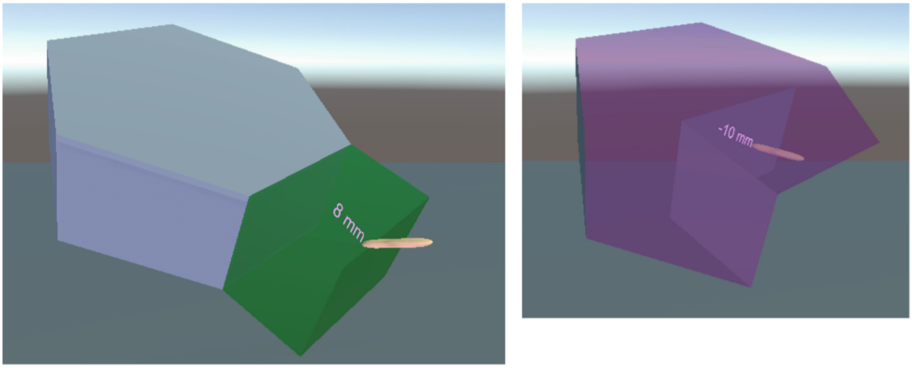

Fig. 10. Moving the faces of the part

Merge Parts
If two parts are selected to be combined the user can align them in the position of their choosing with a limited set of constraint tools available to aid alignment. The merge is then carried out on the under lying BRep models using Boolean operations. This change also combines the parts into one part on the assembly tree.

Add Notes
Notes can be added to the parts to indicate complex features not modelled in their entirety, snap points, and general notes about the part and design decisions.

4.5 Final Comparison of Results

Once the user has finished acting on the advice given they can compare the original and modified designs. This can be in the form of the original and new assembly hierarchies, or the new and old timelines, or in a table. The new models can also be exported.

5 Case Study

In order to test the system, the controller assembly case study from [25] was used. The results and process will be compared. This assembly consists of 16 parts and needs 21 operations to complete the assembly. The initial design can be seen in Fig. 11.

The assembly was analyzed as described in the previous sections and the following results obtained (Fig. 12).

These results are comparable to the ones obtained in the original case study using manual DFA analysis (Table 3).

The next stage of the case study is to act on the generated advice. The starting point for the redesign was to consider all the advice pertaining to the functionality of the assembly parts. This indicated that eleven part merges and or deletions were advised. These were the merging of the metal frame with the plastic cover, the elimination of the strap holding the sensor onto the frame, elimination of the tube connecting the sensor to

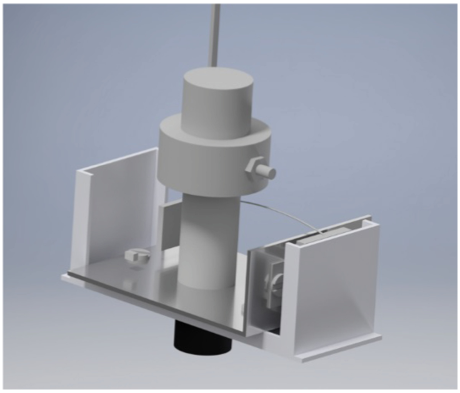

Fig. 11. Original controller assembly

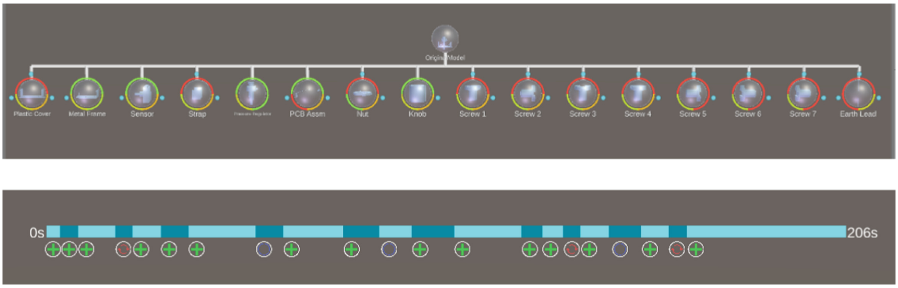

Fig. 12. Assembly tree and time line for original assembly

the pressure regulator, the use of an alternative way of attaching the PCB to the frame/cover, the elimination of the earth lead, the elimination of the nut holding on the knob, and the elimination of all the screws.

To address this advice the first action taken was to redesign the plastic cover to include the functionality of the metal plate (primarily attachment points for the other parts). This included the addition of snap mounting points for the PCB assembly and sensor, alteration to the bottom of the cover to include a place for the pressure regulator to rest, ribs to strengthen the part, and elimination of the screw holes as they are no longer necessary. As this change merged the two parts formerly connected with screws this change was detected and the screws were automatically removed from the assembly. The next alteration made was to alter the PCB to connect directly to the sensor eliminating the need for a cable to be connected across the model alongside mounting the PCB in the cover using snaps eliminating another two screws in the process. The sensor was then mounted on top of the PCB eliminating the strap and the screws holding it on. To eliminate the connector tube a new adaptor nut was created connecting the sensor directly to the pressure regulator.

Table 3. Overview of original analysis results

	Handling code	Insertion code	Function score	Total time
Pressure regulator	30	00	1	3.45
Metal frame	30	02	1	4.55
Nut	00	31	0	9.33
Reorient	–	61	–	4.50
Sensor	30	03	1	7.15
Strap	20	03	0	7.00
Screw ×2	11	31	0	17.10
Apply tape	–	62	–	7.00
Adapter nut	10	51	0	15.10
Tube assembly	42	10	0	9.30
Screw fasten	–	60	–	8.10
PCB assembly	42	03	1	10.80
Screw ×2	11	31	0	17.10
Connector	30	05	0	5.25
Earth lead	42	05	0	8.90
Reorient	–	61	–	4.50
Knob	30	03	1	7.15
Screw fasten	–	60	–	8.10
Plastic cover	30	03	0	7.15
Reorient	–	61	–	4.50
Screw ×3	11	51	0	40.4

Once the functionality advice had been acted on only seven parts were left in the assembly, a major improvement on the original design. The resulting design can be observed in Fig. 13, 14, 15 and in Table 4.

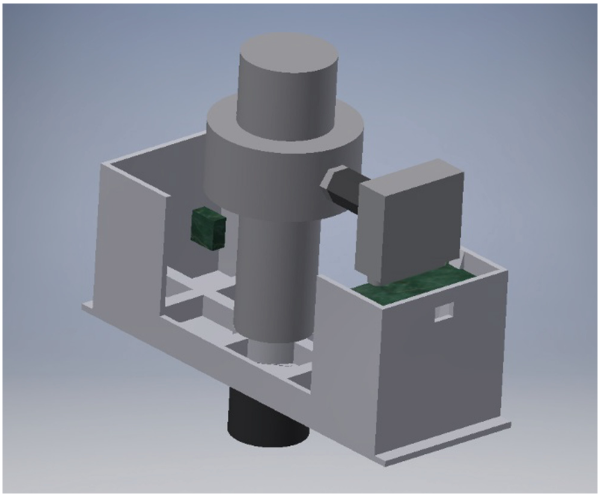

Fig. 13. Redesigned assembly

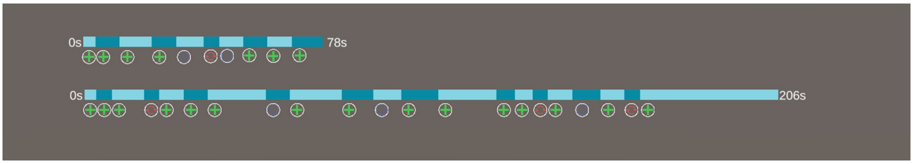

Fig. 14. Comparison timelines of the original and redesigned models

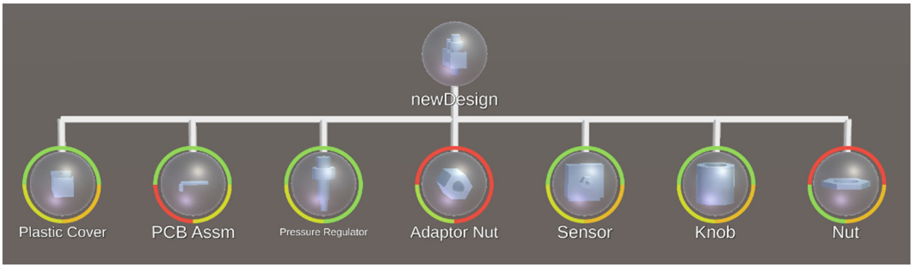

Fig. 15. Finished design

Table 4. Overview of analysis for assembly redesign

	Handling code	Insertion code	Function score	Total time
Pressure regulator	30	00	1	3.45
Plastic cover	30	03	1	7.15
Nut	00	31	0	9.33
Knob	30	03	1	7.15
Screw fastening	–	60	–	8.10
Reorientation	–	61	–	4.50
Apply tape	–	62	–	7.00
Adapter nut	10	51	0	15.10
Sensor	30	31	1	7.25
PCB assembly	42	05	1	8.90

By following the advice given a design that is comparable to the original solution was created. The original design had a DFA index of only 7%, and took 206 s to assemble while the final design has a DFA index of 19% and took only 78 s to assemble.

6 Discussion and Conclusions

The initial analysis of the controller case study shows results that are the same as those calculated in [25] using manual methods, this validates the accuracy of the DFA analysis carried out in the system.

The assembly as analyzed has includes flexible parts, cables, these were modelled as solid inflexible parts. While this provides sufficient information to correctly assign DFA codes to the parts when modelled in their final positions it proves to increase the time needed for modelling by necessitating the remodeling of the part each time the path of the cable needs to be altered.

The model was able to be redesigned within the system demonstrating that the sketch based modelling environment is a viable way of carrying out design modifications for the purpose of DFMA analysis.

7 Future Work

The functionality of the system with regards to the analysis of manufacturability and process planning based on previous work in this area [26].

To further test the robustness and limitations of the system more case studies will be carried out. In addition, user evaluations will be undertaken to test the functionality and usability from a user perspective.

Additional analysis of the manufacturability of the assembly will be integrated into the system.

References

1. Keys, L.K.: System life cycle engineering and DF"X". IEEE Trans. Compon. Hybrids Manuf. Technol. **13**, 83–93 (1990)
2. Dowlatshahi, S.: The role of logistics in concurrent engineering. Int. J. Prod. Econ. **44**, 189–199 (1996)
3. Kuo, T.-C., Huang, S.H., Zhang, H.-C.: Design for manufacture and design for X: concepts, applications, and perspectives. Comput. Ind. Eng. **41**, 241–260 (2001)
4. Read, A., Ritchie, J., Lim, T.: A UNITY sketch based modelling environment for virtual assembly and machining to evaluate DFMA metrics. In: 36th Computers and Information in Engineering Conference, vol. 1B, p. V01BT02A049 (2016)
5. Boothroyd, G., Alting, L.: Design for assembly and disassembly. CIRP Ann. - Manuf. Technol. **41**, 625–636 (1992)
6. Lucas Engineering Systems Ltd: Design for Manufacture and Assembly Practitioners Manual. Version 10. University of Hull (1993)
7. Owensby, E., Shanthakumar, A., Rayate, V., Namouz, E., Summers, J.D.: Evaluation and comparison of two design for assembly methods: subjectivity of information inputs. In: International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, vol. 9, pp. 721–731 (2011)
8. Sturges, R., Kilani, M.: Towards an integrated design for an assembly evaluation and reasoning system. Comput. Des. **24**, 67–79 (1992)
9. Coma, O., Mascle, C., Veron, P.: Geometric and form feature recognition tools applied to a design for assembly methodology. CAD Comput. Aided Des. **35**, 1193–1210 (2003)
10. Mei, H., Robison, P.A.: Adding expert support to assembly-oriented computer aided design tools. Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. **214**, 81–88 (2000)
11. Sanders, D., Tan, Y.C., Rogers, I., Tewkesbury, G.E.: An expert system for automatic design-for-assembly. Assem. Autom. **29**, 378–388 (2009)

12. Tate, S.S.J., Jared, G.E.M., Brown, N.N.J., Swift, K.G.K.G.: An Introduction to the Designers' Sandpit. In: Proceedings of DFM 2000 Design and Manufacturing, pp. 1–7 (2000)
13. Tate, S.J., Jared, G.E.M.: Recognising symmetry in solid models. CAD Comput. Aided Des. **35**, 673–692 (2003)
14. Barnes, C., Dalgleish, G., Jared, G.: Assembly sequence structures in design for assembly. In: Assembly and Task Planning, pp. 164–169 (1997)
15. Brown, N.J., Swift, K.G., Jared, G.E.M., Rodriguez-Toro, C.: Manufacturability in the designers â€™ sandpit. Proc. Inst. Mech. Eng. **221**, 143 (2007)
16. Rodriguez-Toro, C., Jared, G., Swift, K.: Product - Development Complexity Metrics: a Framework for Proactive-DFA Implementation. In: Proceedings of Design 2004, 8th International Design Conference, pp. 483–490 (2004)
17. De Araújo, B.R., Casiez, G., Jorge, J.A., Hachet, M.: Mockup builder: 3D modeling on and above the surface. Comput. Graph. **37**, 165–178 (2013)
18. Coma, O., Mascle, C., Balazinski, M.: Application of a fuzzy decision support system in a design for assembly methodology. Int. J. Comput. Integr. Manuf. **17**, 83–94 (2004)
19. Dalgleish, G.F., Jared, G.E.M., Swift, K.G.: Design for assembly: influencing the design process. J. Eng. Des. **11**, 17–29 (2000)
20. Lim, T., Ritchie, J., Sung, R.: Haptic virtual reality assembly–moving towards real engineering applications. In: Advances in Haptics, pp. 693–723 (2010)
21. Ritchie, J.M., Lim, T., Sung, R.C.W., Corney, J.R., Rea, H.: The analysis of design and manufacturing tasks using haptic and immersive VR - some case studies. In: Talaba, D., Amditis, A. (eds.) Product Engineering : Tools and Methods Based on Virtual Reality, pp. 507–522. Springer, Heidelberg (2008). https://doi.org/10.1007/978-1-4020-8200-9_27
22. Open Cascade. http://www.opencascade.com/
23. Geomagic.com: OpenHaptic Toolkit Overview. http://www.geomagic.com/en/products/open-haptics/overview/
24. Poyade, M., Kargas, M., Portela, V.: Haptic Plug-In for Unity (2014)
25. Boothroyd, G., Dewhurst, P., Knight, W.: Product Design for Manufacture and Assembly. Marcel Dekker, New York (2002)
26. Fletcher, C., Ritchie, J., Lim, T., Sung, R.: The development of an integrated haptic VR machining environment for the automatic generation of process plans. In: Computers in Industry, pp. 1045–1060 (2013)

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