Haptics Interface for Modelling and Simulation of Flexible Cables

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Abstract—Virtual reality systems are becoming a must for product and process design, training practices and ergonomic analysis in many manufacturing industries. The automotive sector is considered to be the leader in applying virtual reality (VR) solutions for real-world, non-trivial, problems. Although, a number of commercial 3D engineering tools for digital mockups exist; most of them lack intuitive direct manipulation of the digital mockups. The majority of these 3D engineering tools are constrained to the interaction mainly with rigid objects which is just half the story. To bridge this gap, we have developed a haptics interface for modelling and simulation of flexible objects. The graphical and haptic user interface developed allows the creation of multiple one dimensional (1D) flexible objects, such as hoses, cables and harnesses. The user is required to provide the mechanical properties of the material such as Young’s modulus, Poisson’s ratio, material density, damping factors, as well as dimensional properties such as length, and inner and outer diameters of the flexible object. Flexilution solver is employed to estimate and simulate the dynamic behaviour of flexible objects in response to external user interaction, whereas Nvidia’s generic physics engine is used to simulate the behaviour of rigid objects. A generic communication interface is developed to accommodate a variety of devices without the reconfiguration of the simulation platform.

Keywords—haptics interface, cable modelling and simulation

I. INTRODUCTION

Virtual reality systems are becoming a must for product and process design, training practices and ergonomic analysis in many manufacturing industries [1]. The automotive sector is considered to be the leader in applying virtual reality (VR) solutions for real-world, non-trivial, problems. Although, a number of commercial 3D engineering tools for digital mockups exist [5], [6]; most of them lack intuitive direct manipulation of the digital mockups. The work presents the design and development of an intuitive Graphical User Interface (GUI) and Haptic User Interface (HUI) for the modelling and simulation of digital mockups including both rigid and flexible objects. An earlier version of the proposed system constrained to the simulation of only rigid objects is presented in [2]. The developed system is haptics technology-based virtual reality system, involving the modelling and simulation of one-dimensional (1D) flexible objects, such as cables, pipes and hoses. This interface generates realistic force reflections that could be observed in the real world by physical manipulation of the modelled objects, such as pipes, cables and hoses.

An intuitive GUI has been developed allowing the users, not familiar with the developed Virtual Reality (VR) system, to operate the system with ease. The GUI developed for the flexible objects simulation platform, as shown in Figure 1 and 2, allows the creation of multiple one dimensional (1D) flexible objects, including hoses, cables and harnesses. The user is required to provide the mechanical properties of the material such as Young’s modulus, Poisson’s ratio, material density, damping factors, as well as dimensional properties such as length, and inner and outer diameters of the flexible object. The Flexilution solver [3] is employed to estimate and simulate the dynamic behaviour of flexible objects in response to external user interaction whereas Nvidia’s generic physics engine is used to simulate the behaviour of rigid objects. In addition, a generic communication interface is developed to accommodate a variety of devices without the reconfiguration of the simulation platform. This interface provides flexibility to incorporate wide variety of haptic devices with range of forces and work envelops suitable for different assembly tasks, and ergonomic analysis and evaluation. The developed interface is capable of accommodating haptic devices from the vendors including SensAble, Haption, force dimension and Novint, as shown in Figure 2.

To create and define the properties of the required simulation model, a simple and intuitive GUI is developed as shown in Figure 3. The developed GUI provides the flexibility of adjusting and changing the simulation and interface parameters including haptics functionality, haptics device configuration, graphics rendering, object dimensions, material properties and simulation parameters. Simulation parameters encapsulates all details regarding simulation behaviour such as gravity, force/torque feedback and collision modes. Graphics rendering includes changing views, colouring, objects rendering, and highlighting modes. Haptics parameters include changing haptic devices, force and speed limits, and operating modes for positional sensors.

The developed interface is a complete lab tool allowing the users to interact with rigid and flexible materials in an interactive manner. The interface can be used for design of the products and assembly processes, ergonomic analysis and evaluation, as well as training of assembly operators in conjunction with our virtual assembly training system [2], incorporating both rigid and flexible objects.

Developed GUI is divided into five distinct features includ-
ing simulation, graphical, haptics, cables and rigid objects. Each of these features consists of a number of parameters required to control the behaviour of the simulation and objects manipulation and is discussed briefly through sections II to III.

II. GRAPHICAL USER INTERFACE

The graphical user interface (GUI) developed for the flexible objects simulation platform allows the creation of multiple one dimensional (1D) flexible objects including pipes, hoses, cables and harnesses. The user is required to provide the mechanical properties of the material including Young’s modulus, Poisson’s Ratio, material density, damping factors, [4] as well as physical measurements consisting of length and inner and outer diameters of the flexible object.

To create and define the properties of the required flexible model, a simple and intuitive graphical user interface (GUI) is developed as shown in Figure 1. The developed GUI provides the flexibility of adjusting as well as changing the parameters involved with haptics functionality and device configuration, graphics rendering and views, cable and the simulation parameters, in run time. As illustrated in Figure 3, the developed GUI presents a tree view with basic parameter branches. Simulation parameters encapsulates all details regarding simulation behaviour such as gravity, force/torque feedback and collision modes. The graphics parameters’ tab includes changing views, colouring, rendering, and highlighting modes. The haptics parameters’ tab includes changing haptic devices, force and speed limits, and operating modes for positional sensors. The cables tree lists all cables in the scene, their parameters, and detailed configurations. Finally, the rigid objects tree lists all objects and their parameters. Influenced by the concerns raised by an internal system review that virtual design scenarios can grow rapidly into complex scenes making it difficult to access a certain feature or change a certain cable parameter, to overcome this problem, a search box has been added to jump directly to the desired parameter. An outlook of simulation and graphics parameters is provided in the next sections.

A. Simulation Parameters

The simulation interface defines the parameters directly linked with the haptics interface, modelled flexible objects and the overall simulation environment as shown in Figure 3 (A). Only binary selection criteria have been provided reflecting enabling and disabling of the parameters. Parameters involved in this interface are:

- Gravity defines the simulation parameter responsible for the effect of gravity on the modelled flexible objects. This parameter affects the behaviour of the virtual cable immediately depending on its density. The higher the density is, the heavier the virtual cable becomes.
- Force Feedback is the haptic device related simulation parameter providing the flexibility of enabling and disabling Cartesian force components to the user. While disabled, the estimated force vectors will not be passed through to the device. Consequently, the device will act as a 3DOF interactive device manipulating the cables without reflecting the forces. The "Reset Haption" button resets the haptic device and disables force feedback in order to avoid abrupt changes that may damage the haptic device or harm the human subject.
- Torque Feedback is also a haptic device related simulation parameter providing the flexibility of enabling and disabling torque force components to the user. The "Reset Haption" button resets the haptic device and disables torque feedback in order to avoid abrupt changes that may damage the haptic device or harm the human subject’s wrist.
- Collision Detection is a simulation parameter responsible for detecting collisions between the flexible and rigid objects consequently generating information for appropriate deformation in the flexible object. This flag will also be disabled while resetting the haptic device to avoid any unpredictable or unstable behaviour.
- Cable Details enables or disables access to the detailed cable properties during the simulation.

B. Graphics Parameters

The designed graphical interface provides access to a number of visual and rendering modes as well as mouse-based controls for navigation and objects transformation as shown in Figure 3 (B). The parameters involved in the visual interface are:

- View defines the camera view of the simulation interface consisting of top, left, front and original views. It is very important to clarify that the haptic device’s positional sensors work in absolute positioning mode. Therefore, changing the views will not change the orientation of the haptic device. Top, Left, and Front views work for screen captures and display purposes. The original view is the only view that is synchronized with the haptic device positioning system.
- Rendering Mode defines different visual forms of representing modelled flexible objects including Gouraud [8], flat [7], wireframe and points. Gouraud shading provides icy smooth look of the cables and allows colouring. Wireframe provides and in depth view of the virtual cables. It is less computationally expensive than Gouraud shading. Finally, the points rendering provides super fast animation. However, it may provide confusing depth perception experience for unexperienced users.
- Colouring defines the enabling and disabling of the colouring scheme of flexible modelling responsible for highlighting the stress/strain on the cable during manipulation. The defined scheme shows the colour variations form green to red highlighting minimum and maximum stress levels on the cable, respectively.
- Graphics Rendering provides a flag to disable graphics rendering in case of performing blind haptics experiments.
- Highlight Selected defines enabling/disabling of colour changes during selection process for manipulation.

Similarly, mouse control consists of
- Mouse Control provides functionality of manipulating objects within the simulation environment using mouse pointer. This helps to perform experiments without the need of a haptics device.
- Horizontal and Vertical restricts the manipulation of virtual objects or the entire view, using mouse. Mouse buttons perform different view transformation. Left mouse button rotates the view; right mouse button translates/panes the view; and finally, zooms into the view. Constraining mouse movements to horizontal or vertical moves allows the user to perform rotations around one axis only. Figure 5 illustrates different examples of the rotations and translation around the three axes.

III. HAPTICS INTERFACE

The haptics interface is responsible for integrating different haptics devices with the simulation including SensAble Phantom Omni, SensAble Phantom Premium, Force Dimension Omega and Haption Virtouse 35-45 6D, as shown in Figure 3.

A. Cables and Rigid Objects

The cables interface provides functionality of creating multiple cables, hoses, pipes and harnesses of desired material defined by the material properties. The properties of the modelled flexible objects can be modified along the length of the modelled object including density, diameter and stiffness while the simulation is in progress. Figure 2 B shows simulation in progress, where a variety of hoses are developed and being manipulated using the haptic device. The user is provided access to the list of section parameters allowing the change of properties of the created flexible object along the length and at any particular section.

1) Virtual Cables: Virtual cables can be added by clicking on the ”Add Cable” button, as shown in Figure 4 (Right). The GUI then opens a dialog box where the user can enter the initial parameter values that describes the virtual flexible object, as shown in Figure 4 (Left). The dialog box also allows the user to load parameters from a stored parameter file describing the flexible object. The ”Leading Pad”, ”Trailing Pad”, and ”Max Young’s Modulus” determine the length of...
start and end of the virtual objects and their stiffness factors. These parameters specify the number of cross sections to have the maximum stiffness according to gripper stiffness correction equations described in expressions 3 and 4. It is important to note that stiffness correction does not apply to cables while the simulation is in progress and require change of “Cable Details” parameter under the simulation parameters section to make it effective.

2) Rigid Objects: Rigid objects can be added by clicking on the "Add Rigid Object" button, as shown in Figure 4 (Right). "Add Rigid Object" event opens a file dialog box listing all 3D objects in the directory. The current interface only accepts .stl graphics format and is planned to be supportive of more generic formats in future versions. Each rigid object is added to the collision engine and a connection with each virtual object is established to maintain the proper collision behaviour between rigid and flexible objects.

IV. CALIBRATION FRAMEWORK

The calibration process is designed to measure the initial orientation of the haptic device after the initialisation of the simulation interface. The cable creation algorithm initializes the transformation matrix of the cable-end to comply with the acquired orientation, as shown in Figure 6. Finally, the transformation matrix of the other end of the cable is calculated using the cable parameters influenced by the initial geometry of the modelled cable.

The initial cable matrix $\hat{M}_c$ is transformed as follows:

$$
\hat{M}_c = M_h^0 . M_v^0 . M_c^0
$$

(1)

where $M_h^0$ is initial orientation matrix of the haptic handle, $M_v^0$ is the orientation matrix of the graphics rendering viewpoint, and $M_c^0$ is the initial matrix of the virtual cable. The initial orientation matrix $M_h^0$ of the haptic handle is calculated from a quaternion vector $q = \langle x, y, z, w \rangle$ as

$$
M_h^0 = \begin{pmatrix}
1 - 2y^2 - 2z^2 & 2xy + 2zw & 2xz - 2yw & 0 \\
2xy - 2zw & 1 - 2x^2 - 2z^2 & 2yz + 2wx & 0 \\
2xz - 2yw & 2yz - 2wx & 1 - 2x^2 - 2y^2 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}
$$

(2)

A. Stiffness Correction

It has been noticed that the cables are generally held by human using tight fist grasp to gain more control during stretching, rotating and fitting tasks, as shown in Figure 5 (B). This creates an offset from the tip of the cable to be used to calculate the forces reflected to the user in a realistic manner, since the structural geometry and physical parameters...
are different at the end of the cable and the offset, as shown in Figure 5 (C). To maintain realistic behaviour, the stiffness factor at the cable end has to be increased to replicate the human grip and force the virtual cable to behave as a gripped cable as illustrated in Figure 5 (D). The number of cross sections \( N_{CS}' \) with increased stiffness is calculated according to the following linear mapping equation:

\[
N_{CS}' = \frac{d}{L} N_{CS}
\]  

(3)

where \( L \) is length of the cable, \( N_{CS} \) the total number of cross sections used in the simulation, \( d \) is the displacement of the users grip from the tip of the haptic handle, and \([\cdot]\) is the floor operator. Assuming that the handle is totally separated from or added to the virtual cable, the cable is modelled with a length of \( L + d \) and \( N_{CS}' \) is then calculated as follows:

\[
N_{CS}' = \left\lfloor \frac{d}{L + d} N_{CS} \right\rfloor
\]  

(4)

Forces cannot be measured at the end of the virtual cable as shown in Figure 5 (C). Instead, forces/torques measured at the end of user’s palm as illustrated in Figure 5 (D). This is where the user’s wrist and arm feels the torques and forces, respectively.

B. Damping Correction

During calibration, the transformation matrix of the haptic device imposed directly to the virtual cable causes a sudden twist at the tip of the cable. This over twisting caused the cable to exert an extremely strong torque to the user’s wrist causing an unstable experience and nullifying the force calculated by
the rest of the cable. This instability issue is modelled as a damping problem to minimize the resonance of force/velocity vectors. A negative force vector has been calculated based on the velocity at which the haptic pointer is moving as follows;

$$F_d = -d\nu$$ (5)

where $F_d$ is the damping force, $d$ is the damping factor, and $\nu$ is the haptic pointer velocity. This solution maintained a stable experience in most scenarios. However, it highlighted another hardware limitation of haptic devices. Haptic devices do not map their work envelope linearly. Due to the design limitations the haptic work envelope features faster loose sampled coordinates at its end and finer sampled coordinates close the origin. This problem caused instabilities of even higher magnitude at the ends of the work envelope. Figure 6 (Left) illustrates how work envelopes of haptic devices look. In order to solve this problem, the 3D coordinates acquired from haptic devices are mapped from polar to linear coordinates to achieve a linear work envelope and linearly mapped velocities as shown in Figure 6 (Right).

V. CONCLUSION

In this work we present the design and development of haptics enabled modelling and simulation of 1D flexible materials, such as cables, hoses and harnesses. The developed system uses Flexilution solver to calculate accurate deformations of

the 1D flexible objects in response to external user interaction. The developed system can be used to simulate the behaviour of flexible objects while perform cable routing, path planning, designing assembly operations within the ergonomic constraints, etc. With its generic interface, the developed system can be a great tool for manufacturing sector requiring product assemblies including automotive and aerospace industries.

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REFERENCES


