

Spatial Mechanism Design in Virtual Reality With Networking

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Mechanisms are used in many devices to move a rigid body through a finite sequence of prescribed locations. The most commonly used mechanisms are four-bar planar mechanisms that move an object in one plane in space. Spatial mechanisms allow motion in three-dimensions (3D), however, to date they are rarely implemented in industry in great part due to the inherent visualization and design challenges involved. Nevertheless, they do provide promise as a practical solution to spatial motion generation and therefore remain an active area of research. Spatial 4C mechanisms are two degree-of-freedom kinematic closed-chains consisting of four rigid links simply connected in series by cylindrical (C) joints. A cylindrical joint is a two degree-of-freedom joint, which allows translation and rotation about a line in space. This paper describes a synthesis process for the design of 4C spatial mechanisms in a virtual environment. Virtual reality allows the user to view and interact with digital models in a more intuitive way than using the traditional human-computer interface (HCI). The software developed as part of this research also allows multiple users to network and share the designed mechanism. Networking tools have the potential to greatly enhance communication between members of the design team at different industrial sites and therefore reduce design costs. This software presents the first effort to provide a three-dimensional digital design environment for the design of spatial 4C mechanisms. [DOI: 10.1115/1.1481363]

Introduction

Virtual reality techniques are increasingly being applied to design of products and systems. An abundance of applications can be found in the current literature, including VR applications for product assembly methods planning [1,2,3], telesurgery [4], ergonomic design of products [5], fluid systems analysis [6,7], interactive structural shape design [8], vehicle simulation [9], rehabilitation aid design [10], parts feeding system design [11], power plant design [12], and others. The focus of the work presented here is on the development of a virtual environment for spatial mechanism design.

Motion synthesis of mechanisms relies on the designer's ability to specify desired locations of an object and visualize relative motion of the resultant mechanism. Traditionally, mechanism design has concentrated on synthesis of planar motion mechanisms. Planar mechanism synthesis involves two-dimensional (2D) display and interaction, and this is well suited to the traditional HCI of a computer monitor, keyboard and mouse. However, designing spatial mechanisms requires the designer to visualize and interact with the mechanism in three dimensions, which is difficult using the traditional HCI. Virtual Reality (VR) technology provides a three-dimensional environment in which to interact with digital models. Thus, this research focuses on the use of VR for the design of spatial mechanisms.

Models viewed using a traditional HCI are not drawn in real size and cannot be manipulated in a natural way. VR allows the user to view the real size models and interact with the models with a position sensor to track head motion and a wand or instrumented glove, which would also be equipped with a position sensor. The head position and orientation are used to compute the viewing perspective for the computer display. This is in contrast to the traditional HCI where the user manipulates a desktop mouse and types on a keyboard to interact with digital models.

Osborn and Vance [13] developed SphereVR as the first VR environment for the design of spherical four-bar mechanisms. SphereVR had the user place coordinate frames on a sphere. The

solution code for the mechanism synthesis of SphereVR was based on Suh and Radcliffe's displacement matrix method [14]. The SphereVR spherical mechanism design program was followed by VEMECS (Virtual Environment for MEchanism Synthesis) [15]. VEMECS used solution algorithms from SPHINX, a monitor-based spherical mechanism design program developed at the University of California, Irvine [16]. In related work, VEMECS and SPHINX were used as the basis to evaluate the difference between using monitor-based software and virtual reality to design spatial mechanisms [17].

Isis followed VEMECS as a design tool for spherical mechanism synthesis in a VR environment [18]. Isis, like VEMECS, used SPHINX synthesis and analysis routines. Isis improved upon VEMECS by providing users the ability to use Iowa State University's C2 virtual environment and the ability to import digital models of the surroundings and the part geometry to aid in the design task. The C2 facility is a 12-foot by 12-foot virtual environment room where stereo images are projected on three walls and the floor. These two features made the design environment more closely resemble the actual operating environment for the final mechanism.

The program described here, VRSpatial, is a VR software program developed at Iowa State University and Florida Institute of Technology to design spatial 4C mechanisms. The task is to design a spatial 4C mechanism in a VR environment and to share the designed mechanism with another user through a network. Four locations are prescribed and then a set of solutions for the spatial motion generation task is computed. The user can select a solution and watch as the mechanism is animated. Users at a remote site are then able to watch as the mechanism is animated. The solution routines used here are the most current routines from SPADES 1.0, a monitor, mouse and keyboard-based spatial 4C mechanism design application developed at Florida Institute of Technology [19].

VRSpatial was developed to allow the user to walk into a three-dimensional space, specify the four locations using three-dimensional hand movements, synthesize the mechanism and then move around in the space to evaluate the mechanism's motion. All of this is performed in a virtual environment where geometric

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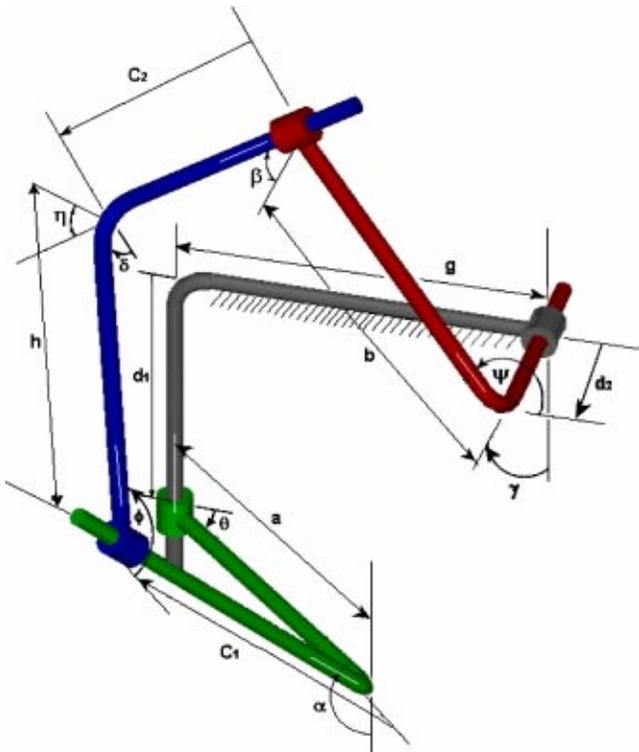


Fig. 1 A spatial 4C mechanism

models of objects in the design space are displayed. In this way, the user is designing the mechanism while in a virtual representation of the working space of the final design.

Spatial 4C Mechanisms

A spatial 4C mechanism consists of a closed linkage with four rigid links connected by four cylindrical (CCCC) joints (Fig. 1). A cylindrical joint rotates and slides along its axis and therefore has two degrees-of-freedom. The VRSpatial program is developed for four-location motion generation of spatial 4C mechanisms.

VRSpatial Virtual Environment and Interactions

The VRSpatial program was designed for display in Iowa State University's C2 facility (Fig. 2). The C2 is a 12×12×10 foot room where stereo images are projected on three walls and the



Fig. 2 Iowa State University's C2 facility



Fig. 3 Collaboration in the C2 facility

floor. Four Barco 1208 projectors are used to project the images. CrystalEyes® shutter glasses are used to provide a stereo image. These glasses consist of LED lenses that are synchronized with the computer display to alternately turn clear and opaque to correspond to the left-eye and right-eye images displayed on the screen. This active stereo technology results in very realistic stereo imaging. The C2 has a three-dimensional sound system and 3D interaction capabilities provided by various input devices including a wand and a glove. Two Silicon Graphics Power Onyx computers, each equipped with four Infinite Reality graphics pipes and twelve R10000 processors provide the computer capacity for the C2. Ascension Flock of Birds® trackers are used to provide position and orientation information to the program. These devices use electromagnetic fields to determine the position and orientation of a receiver in the environment. Receivers are placed on one interaction device and on one set of CrystalEyes® glasses. The main user wears the glasses and holds the interaction device. As this user moves in the environment, the position and orientation of the tracker receivers are continually sent to the program to be used to redraw the correct viewing perspective on the screens.

The C2 environment works well where collaboration with other users in a virtual environment is desired. Multiple users can be present in the C2 facility at the same time. The main user wears the tracked glasses and others in the environment wear additional CrystalEyes® glasses. Figure 3 shows two users in the C2 during the design of a spatial 4C mechanism. Because all users wear simple stereo glasses, participants can see both the stereo images and the other people in the C2 environment. This allows for easy interaction among users and fosters collaboration within the VR environment.

In VRSpatial, interaction is performed using a Fakespace PINCH™ Glove. The PINCH™ Glove has conductive material attached to the fingertips, thumb and palm of the glove to register contact between a user's fingers, palm and thumb. Gestures are used to control actions in the virtual environment. Because a person's real hand sometimes obstructs the virtual objects, a digital hand model is used in the environment to correspond to the location of the participant's hand in space.

The software platform for VRSpatial is WorldTooKit®. Menus are used to provide more options for interaction with the VR environment. These menus are used to control the tasks in the virtual environment. The menus are 3D objects consisting of a menu bar and text items (Fig. 4). The main menu can be opened at any time during the design process by pressing together the pinky finger and the thumb. A menu can be repositioned in space by intersecting the virtual hand model with the menu bar and grasping the menu bar using the first finger and the thumb. This allows the user to move the menu to a location in the virtual environment

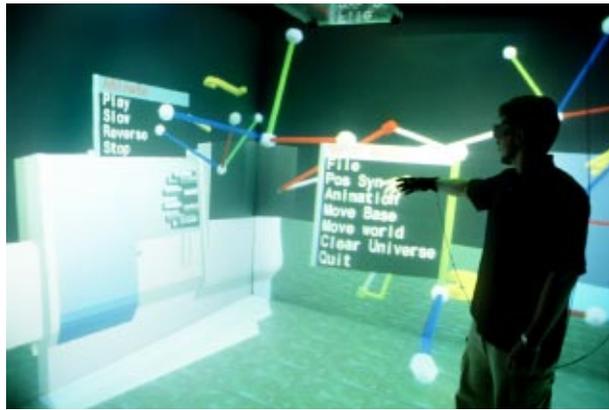


Fig. 4 VRSpatial main menu

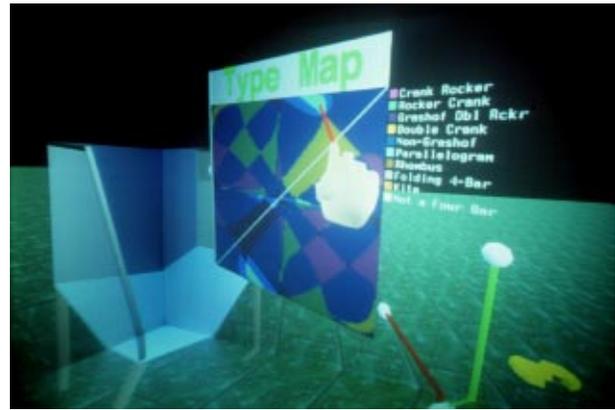


Fig. 6 Type map

that is convenient. A menu option is selected by intersecting the virtual hand model with the menu option and then making a gesture of touching the second finger to the thumb.

Kinematic Synthesis of Spatial 4C Mechanisms

Synthesis of spatial 4C mechanisms is based on the spatial generalization of the classical Burmester center and circle point curves of planar kinematics and the center and circle axis cones of spherical kinematics [20]. The results of the spatial generalization are referred to as the fixed and moving congruences. These congruences are sets of lines that define the axes of CC dyads that guide a body through four prescribed locations in space. A compatible pair of fixed and moving lines or axes maintains a constant normal distance and angle in each of the four locations of the moving body. The spatial triangle technique developed by Murray and McCarthy [21] and Larochele [20] is used in VRSpatial to compute the congruences resulting in a parameterized set of lines.

The first step in defining the design problem is to import models of the surrounding geometry into the virtual environment. These could be models of machine tools, other parts on an adjacent product, assembly fixtures, etc. Then, the part that is to be moved by the mechanism is loaded. Once this part is placed in a desired location, another instance of the part is generated and the user places this part in the next location. This continues until four representations of the part that is to be moved by the mechanism have been located (Fig. 5). The locations can be modified and then numbered 1, 2, 3 and 4 to indicate the order of the movement.

The program calculates all possible mechanisms for the four locations specified and displays the results in the form of either a type map or congruence planes. These options are explained in the following sections.



Fig. 5 Location placement

Type Map. The synthesis solution can be presented in a 2D plot referred to as a “type map.” The type map displays the solutions from the synthesis in a color-coded format showing the mechanism types [22]. Spatial mechanisms are classified according to the mechanism type of their corresponding spherical image. The spherical image is a spherical four-bar mechanism with link lengths equal to the angular twist of the links of the spatial 4C mechanism [23]. The type map generated by VRSpatial for one set of four locations is shown in Fig. 6. One axis of the map represents one choice of dyad and the other axis represents the second choice. Choosing a point on the type map is equivalent to selecting two pairs of corresponding planes from the fixed and moving congruences. Each pair of planes defines a CC dyad with one fixed C joint axis and one moving C joint axis.

To select a point from the type map, a pointer is drawn from the virtual hand model after the pointer gesture has been made by the user. A user moves the pointer in contact with an area of the type map to select a mechanism. Releasing the gesture selects the mechanism from the type map. Once a mechanism has been selected, the solution is drawn on the models in the virtual environment. Different mechanisms can be chosen until the user gets a satisfactory mechanism.

For the type map representation of the four location synthesis solutions, spatial 4C mechanisms are analyzed to eliminate order, branch, and circuit defects in motion generation tasks [24]. A mechanism is said to suffer from branch defects if it enters a stationery configuration that requires an additional mechanical input to guide the moving body as desired. Circuit defects occur when a solution exists but the mechanism must be disassembled and reassembled to move between two desired locations. Mechanisms that have these defects are filtered so that the type map is darkened where these defects occur. Solutions that pass the branch and circuit defect tests remain bright on the type map, guiding the user to select good solutions.

Fixed and Moving Congruences. The solution from the synthesis can also be presented as fixed and moving line congruences [20]. The moving line congruence is the set of all moving C joint axes that can be used in a 4C mechanism to guide a body through the four locations. The fixed line congruence is the set of all corresponding fixed C joint axes. There is a one to one correspondence between the fixed and moving line congruences associated with the four spatial locations. Therefore, selecting one line from either congruence defines a CC dyad, or half of the 4C mechanism.

The fixed and moving line congruences are sets of infinite planes, represented here as sets of planes in the virtual environment with a single central line. The moving congruences are represented by yellow planes and the fixed congruences are repre-

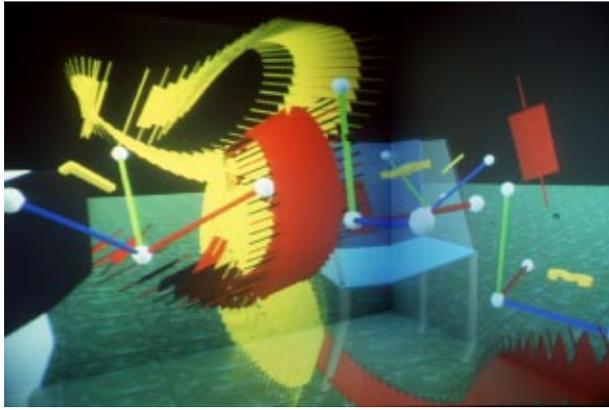


Fig. 7 Fixed and moving congruences

sented by red planes (Fig. 7). The user has to make two selections from the congruence planes to completely define a solution mechanism.

When a choice is made from the congruences, the axis of the chosen plane turns blue. A dyad is picked from the moving plane congruences and another from the fixed plane congruences to form a complete spatial 4C mechanism. Picking these lines in the virtual environment is a very simple task when compared to picking them using a traditional monitor, mouse and keyboard. In VRSpatial, the main user walks around to where he/she can reach out with the wand and move the input device such that the virtual hand model intersects with the desired line. Whenever the virtual hand intersects with the representation of a congruence, the congruence is selected and the corresponding congruence is highlighted as well. The user can interactively select from the entire set of lines by simply moving around in the virtual space.

After a mechanism has been chosen from the type map or from the congruences, it is animated to verify it completes the task as required. To complete the task, the mechanism should move the object through the four locations. The user can observe the motion of the mechanism to see whether the mechanism collides with objects in the virtual space and whether it goes through the locations in the required order. The user with the tracked glasses can move around the design and investigate the mechanism from different angles. After getting a desirable mechanism, an output file of the mechanism generated can be saved by selecting the *Save Mechanism* option from the File menu.

Networking With VRSpatial

VRSpatial sends location translations and rotations, mechanism link lengths, and joint translations and rotations over the network to other users using the World-To-World software from Sense8. Only one of the users in the VR network is allowed to input the initial location information and to design a mechanism. The location information is sent out to the simulation server and the other users receive the update for the location and the designed mechanism. The update for the location and mechanism data is reflected at the networked site as soon as a change is made. However, the networking system speed will determine how fast the changes are received by the other users. After the mechanism has been designed, any of the networked users can animate the mechanism using the menu. The animation data is sent to all the users and they will see the mechanism animated in their VR environment.

Networking between two virtual environments currently requires that the two virtual environments have similar interaction devices. VRSpatial networking was tested between two computers by loading a mechanism previously designed in the C2 virtual environment. Both computers displayed a monitor-based window

showing the mechanism. When either of the users animated the mechanism, the other user saw the mechanism animated on his/her computer as well.

Example

Figure 8 shows a summary flow chart of the procedure used to design a spatial 4C mechanism. The gray boxes indicate the sections of the program that utilize routines from SPADES 1.0. Two options are available to design a new mechanism: the first choice is to load a base geometry and then load the movable geometry and the second choice is to load just the movable geometry. After placing the locations and setting the order, the user can choose to find congruences or to create a type map.

VRSpatial was used to design a 4C mechanism to pass through four locations. A lathe and a table were loaded as the base geometry. The design task was to design a mechanism that would move a workpiece from the lathe to the table. Four locations were specified, with the first location being on the lathe and the fourth location being on the table. After the locations were specified, the order in which the mechanism should go through the locations was set. There were no solutions that satisfied the required task on the first attempt to design a mechanism to go through the four locations. Locations 2 and 3 were adjusted and the type map regenerated. Mechanisms were selected from the type map and animated until a satisfactory mechanism was found.

Figure 9 shows a spatial 4C mechanism designed using the VRSpatial software and the four locations that were specified.

The X-, Y-, and Z-axes are drawn in red, green, and blue, respectively, in each location of the moving workpiece. The driving link is green, the driven link is red and the coupler and fixed links are gray. A coupler extension attached to the coupler link has an axis frame attached to it. This frame moves through the locations during the animation to verify the motion of the mechanism.

Results and Conclusions

This program is the first virtual environment for the design of spatial 4C mechanisms. Several users have designed mechanisms using VRSpatial. Their comments consistently indicate that the C2 virtual environment provided them with a three-dimensional workspace that facilitated collaboration with their colleagues and helped them to specify the design as well as understand the final solution. It was very intuitive to place the part to be moved into locations around the surrounding geometry. Having the geometry displayed in stereo gave the users additional information on how the part would move through space when it was attached to the mechanism. Being surrounded by congruences gave the users a better feel for the three-dimensional nature of the design space. Animating the linkage provided them with a way to verify that the final mechanism succeeded in guiding the desired part into its desired locations.

When users were networked, users at different locations were able to view the same model. When one of the users manipulated the model, the other users viewing that model were able to see the updated manipulated model. This allowed users to discuss the design model even though they were not in the same location.

Future Work

VRSpatial provides an excellent three-dimensional interactive environment in which to design spatial 4C mechanisms. This environment makes it easy to place design positions, select design parameters, and examine the resulting mechanism. One of the remaining problems is that it is difficult to find a mechanism which moves in an acceptable motion. Filters have been applied to eliminate branching and incorrect order of the positions, however, some of the candidate paths contain large loops, which occur between two adjacent positions. Mechanisms with this feature are not feasible designs in a practical sense. In the future, additional information must be provided to the designer to guide the design of feasible mechanisms.

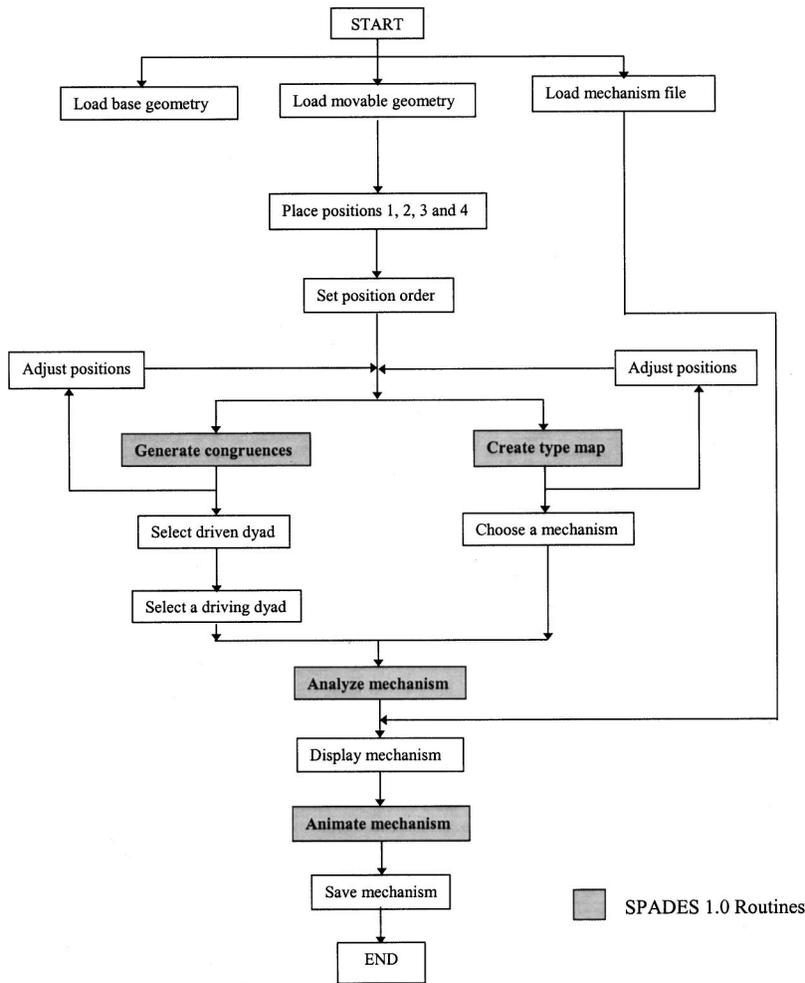


Fig. 8 Flowchart

Another small limitation of VRSpatial is that it requires the user to specify four locations to synthesize the solutions. Often, only the first and last locations are critical and the intermediate locations are somewhat arbitrary. In the future, VRSpatial can be improved to allow the user to only specify two locations and then two additional locations will be interpolated to yield useful solutions, which do not suffer from order, circuit, or branch defects.

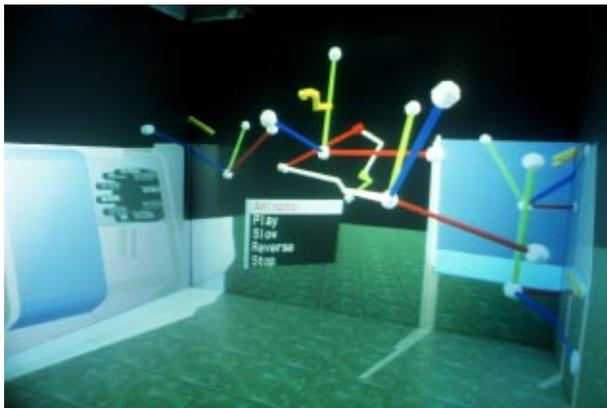


Fig. 9 A spatial 4C mechanism designed using VRSpatial

The method of selecting lines from the congruences can also be improved. The user should be able to pick any line from the selected plane, not just the line that is displayed currently. After this line is selected, the other lines of the congruences could be color coded to indicate what type of mechanism would result from their selection. This in essence would combine the information currently provided in the type map method with the selection of the congruences and provide the designer with more information about the resultant mechanism.

Another possible improvement to VRSpatial would be to add the capability to affect small changes in the definitions of one or more locations. Often in motion generation tasks some locations must be reached exactly while others can be modified while still accomplishing the overall prescribed task. A method for implementing such small location changes needs to be developed for the virtual environment.

The software should be tested as a networking tool between two virtual environments with similar interaction devices. VRSpatial was only tested between two computers by loading a mechanism that was designed in the C2 virtual environment. Recently, the C6 virtual environment was completed at Iowa State University, which will allow networked applications between the two facilities. Such improvements can lead to better understanding of the design process and lead to useful applications.

Acknowledgments

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