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Multi-sensory user interface for a virtual-reality-based computer-aided design system

Chi-Cheng P Chu, Tushar H Dani and Rajit Gadh*

The generation of geometric shapes called 'geometric concept designs' via the multi-sensory user interface of a virtual reality (VR) based system motivates the current research. In this new VR-based system, geometric designs can be more effectively inputted into the computer in a physically intuitive way. The interaction mechanism is similar to the way in which industrial designers sit and discuss concept design shapes across a table from each other, prior to making a final decision about the product details. By using different sensory modalities, such as voice, hand motions and gestures, product designers can convey design ideas through the VR-based computer-aided design (CAD) system. In this scenario, the multi-sensory interface between human and computer plays a central role with respect to usability, usefulness and accuracy. The current paper focuses on determining the requirements for the multi-sensory user interface and assessing the applications of different input and output mechanisms in the virtual environment (VE). In order to evaluate this multi-sensory user interface, this paper formulates the typical activities in product shape design into a set of requirements for the VR-CAD system. On the basis of these requirements, we interviewed typical CAD users about the effectiveness of using different sensory input and output interaction mechanisms such as visual, auditory and tactile. According to the results of these investigations, a nodal network of design activity that defines the multi-sensory user interface of the VR-CAD system is determined in the current research. The VR-CAD system is still being developed. However, voice command input, hand motion input, three-dimensional visual output and auditory output have been successfully integrated into the current system. Moreover, several mechanical parts have been successfully created through the VR interface. Once designers use the VR-CAD system that we are currently developing, the interface requirements determined in the current paper may be verified or refined. The objectives of the current research are to expand the frontiers of product design and establish a new paradigm for the VR-based conceptual shape design system. © 1997 Elsevier Science Ltd

Keywords: virtual reality, multi-sensory user interface, conceptual shape design, sensory interaction mechanism

I-CARVE Lab, Department of Mechanical Engineering, University of Wisconsin–Madison, 1513 University Ave., Madison, WI 53706, USA
*To whom correspondence should be addressed
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INTRODUCTION

Until recently, computer-aided design (CAD) systems have limited designers' ability to create concept shape designs in a non-intuitive way. Designs are typically created by using a combination of keyboard and mouse (or other type of digitizer) input. Although the designs themselves are three-dimensional (3D) in nature, the keyboard is a one-dimensional device and the mouse is a two-dimensional (2D) device. Thus both restrict the designer when creating objects to using point-wise input (i.e. points entered using a pointing device such as a mouse). In addition, the designer must have a prior idea about the detailed position and orientation of the design features before he/she can manipulate them in the design space. This process makes current CAD systems difficult to use for concept design generation.

Moreover, concept shape designs are usually generated by design engineers who often lack expertise in using industrial CAD systems. Therefore, while they can request a draftsperson to create the concept shape, frequently this is time consuming and expensive—especially in the concept stages where designs change very often. The other alternative, using paper and pencil for creating concept shapes, makes it difficult to communicate ideas to others and lengthens the design time because the shape designs have to be recreated in the CAD systems.

Interactive 3D visualization is another area in which current CAD systems are limited. In most current CAD systems, only one transformation can be performed at a time while viewing the part, e.g. either a single rotation or a single translation. These mathematically precise operations are often not intuitively obvious and have to be visualized before generation of the product design. Thus, it is difficult for a designer to ascertain the combination of rotations and translation needed to get to the desired view without trial and error.

On the other hand, a virtual reality (VR) based CAD system would allow the user to 'grab' an object and manipulate it as if holding it in his/her hand—physically, a more natural and intuitive interaction. This approach allows concept shape designs to be created on a computer by using natural interaction mechanisms such as voice and gestures. The present research determines the requirements in the VR-CAD system and investigates the usefulness of different combinations of three sensory input and output mechanisms: visual, auditory and tactile. The input mechanism allows the user to navigate and manipulate objects in the design space by using eye motion (visual), voice commands (auditory) and hand motion/gesture (tactile). The output mechanism provides the user 3D stereoscopic vision (visual), auditory feedback (auditory) and haptic feedback (tactile). Interviews with typical CAD users concerning the effectiveness of different sensory interaction mechanisms forms the foundation of the results. From these results, a network of nodes that define the design activities in the VR-CAD system is determined. Each node in the network corresponds to an activity and defines a set of sensory input/output mechanism for the designer to create and manipulate the product design. By traveling through this nodal network, the designer is navigating the space of activities he/she can do. The designer may interact with the design space through a physically intuitive communication with the VR-CAD system. The designer may talk to the system through the voice command and manipulate objects in the design space through hand motion/gesture. The system will respond to the user input with 3D stereoscopic images, auditory feedback and tactile/force feedback to give the designer a realistic sensory feeling about the design space.

RELATED WORK

A multimodal interface between human and computer allows the user to perform design activities in the virtual environment in an intuitive manner. Most current research on multimodal interfaces focuses on voice recognition and the interpretation of gestures, intonation, facial expressions and gazes for communication with a virtual environment.

In AT&T Bell Laboratories, David Weimer[1] uses a VPL DataGlove to track hand positions and speech recognition to create a synthetic visual environment for CAD and teleoperation activities. This system uses a virtual control panel combined with gestures and speech to create parts. The gestures are used to select items from the menu and the speech commands are used for invoking system commands. The Media Laboratory at the Massachusetts Institute of Technology[2,3] is exploring ways in which the three modes of speech, gesture and gaze can be combined at the interface to allow people to interact in real time with a graphics display by pointing, looking, asking questions and issuing commands. The IVY system[4], developed by Kuehne and Oliver at Iowa State University, allows users to interact with both geometric and abstract representations of the assembly using a head-coupled display, six degree-of-freedom trackers and an instrumented glove.

Other VR applications, such as the DesignSpace system[5] at Stanford University, allow conceptual design and assembly using voice and gesture in a networked virtual environment. The 3 Draw system[6] uses a 3D input device to let the designer sketch out ideas in three dimensions. The JDCAD system[7] uses a pair of 3D input devices and 3D interface menus to allow 3D design of components. Fadel *et al.*[8] proposed a 3D CAD system by performing solid operations and visualizations for support structures in the virtual environment. Yeh and Vance[9] combine virtual reality and engineering design to allow analysis and optimization of structures. The optimal design of a cantilever beam is presented to illustrate the interactive sensitivity in a virtual environment. Connacher and Jayaram[10] enable planning simulation and design of the assembly processes through the virtual environment. Dani and Gadh[11-13] have developed a framework for a virtual-reality-based conceptual shape design system. This approach makes use of VR hardware and software technology to provide an interactive 3D environment in which the designer can use a combination of hand gesture, voice input and keyboard to create and view mechanical components. Their focus is on the development of the geometric modeling paradigm to support the virtual design environment.

Over the past few years, interest in multimodal interaction for part design through the virtual environment has steadily increased. Interaction architecture for multimodal systems provides a communication scheme for concurrence of input data processing. Quek[14] at the University of Illinois–Chicago performs gesture interpretation on a dynamic vision system via an event detection algorithm that segments and tracks the motion of the LED-adorned glove in front of a video system over multiple display frames. Voice commands are used to segment gesture epochs and to clarify the gesture categories. Nigay and Coutaz[15] analyze the integration of multiple communication modalities within an interactive system. Their research presents a classification space that describes the properties of both input and output interfaces of multimodal systems. Gilner[16] is developing a theoretical basis for multimodal interface and auditory interface (graphics and sound) issues, and the temporal and dynamic aspects of the abstract objects that are active in the interface. The system consists of microworld environments for experimentation, used as testbeds for controlled experimentation to validate the theoretical aspects of the interface design process. Pausch[17,18] integrates multimodal input from a human to a computer into higher-level semantic actions. He examines software architectures that deal with combinations of simultaneous input streams. Other related research for VR interfaces can be found in Kakadiaris[19], Wickens[20], DeFanti[21], Hardwick[22], Badler[23], Mapes[24], Luecke[25], Reed[26] and Tuner[27]. Research using computer neural networks and artificial intelligence for voice/speech recognition in the VE can be found in Nakatani[28], Chau[29], Mostow[30], Zhao[31] and Anderson[32].

However, there has not yet been a systematic study of the requirements of a design system; one which maps them to the needs of the interaction mechanisms. This paper provides such a study by investigating the activities of product design, determining the requirements for the VR-CAD system, and evaluating the interaction mechanisms according to the stated requirements.

REQUIREMENTS FOR MULTI-SENSORY USER INTERFACE

Product shape design typically consists of a set of activities that result in both the generation of assembly and component design. Although this is a complex process, this paper focuses on the most common tasks needed for creation of the concept shape of the product, such as creating the geometric configuration of the part and assembly design. In this design system, the designer, sitting in a virtual reality environment, creates three-dimensional shapes by voice commands, hand motions and finger motions, grabs objects with his/her hands and moves them around; detaches parts from assemblies and attaches new parts to assemblies. In this scenario, the multi-sensory

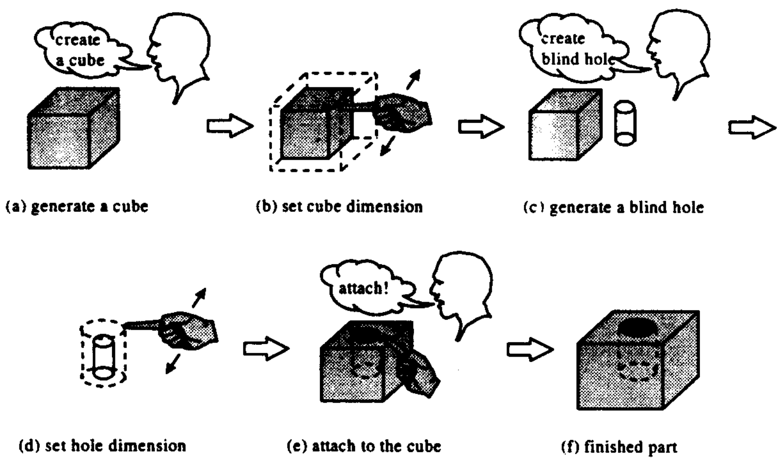


Figure 1 Generation of a cube with the blind hole

interface between the human and the computer plays a very important role with respect to usability, usefulness and accuracy. In order to evaluate the multi-sensory interface, this paper formulates the typical activities in product shape design into a set of requirements for the multi-sensory interface of the VR-CAD system.

Typically, there are three principal classes of unit activities in product shape design: generation, modification, and review. *Generation* starts with a null state of design and generates a new design. *Modification* modifies an existing design. *Review* examines a design or a certain aspect of the design without the intent of modifying it. These three activities can be carried out with respect to either a part or an assembly.

Part and assembly generation

A part or a component is a unit object that belongs to an assembly. A part typically contains a variety of shapes on it, which are known as features. To generate a part shape, the designer may issue a verbal command to the CAD system to obtain a default part shape and add features on it. As parts or features are presented in the design space, the designer may set the dimensions, locations and orientations of the part or features. After the dimensions, locations and orientations of the part are set, the designer can attach features to the part.

Figures 1a–f show the generation of a cylindrical blind hole on the top surface of a cube as an example of part generation. First, the user issues a voice command "create a cube" (*Figure 1a*) or performs a hand gesture to call a default cube shape from the system database. Then, she/he uses hand positions to resize, move or rotate the cube to the desired shape and location in the virtual environment (*Figure 1b*). Second, she/he creates a blind hole (*Figure 1c*) by voice command or hand gesture, resizes the blind hole by hand positions (*Figure 1d*), rotates or moves the blind hole to the top surface of the cube, and issues a command like "attach" to attach the hole to the cube (*Figure 1e*). (The designer may also attach the blind hole to the cube before she/he resizes or rotates it. However, the resizing or rotate operations for the hole on the cube are included in the class of 'Part and Assembly Modification', which will be discussed in the next section.)

Some shape features do not possess a standard or canonical form. Creation of a feature, such as a free-form surface, may require the designer to explicitly 'describe' the feature to the computer by tracking the hand motions or by using vocal instructions. Hand motions may be used to sweep through the design space to create the free-form surface as shown in *Figure 2*. The interface mechanism should also allow the users to move their hand back and forth to remold the surface to the desired shape like molding a clay. (This is where the tactile feedback to the hand is important in the sensory mechanism.)

Assembly generation involves retrieving existing parts or sub-assemblies, which may have been previously created and stored in the system database, moving or rotating them and finally attaching them together in assembled configurations. Existing design paradigms for creating assemblies require designers to define the mating surfaces on the part or assembly through the traditional 2D interfaces (screen, mouse and keyboard) so that the system can attach them together. These operations are often time consuming owing to the limited capabilities of a 2D interface for performing 3D operations.

However, use of a virtual environment interface allows a user to perform assembly generations in an intuitive manner. The user can hold two parts or assemblies in the virtual space, move them by hand, and take them very close to each other in a position where they will be assembled as shown in *Figure 3*. He/she then commands

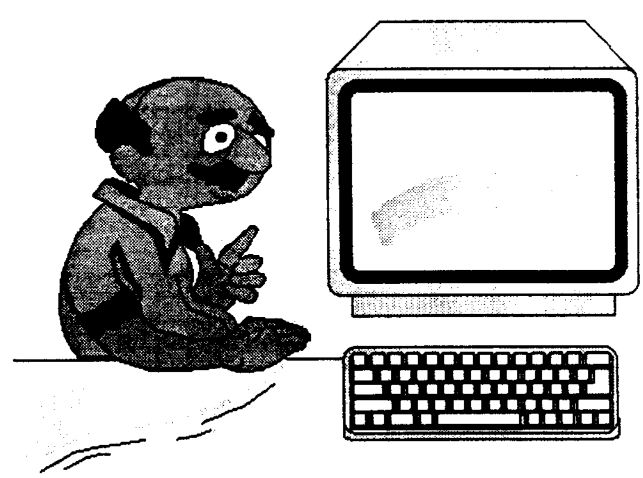


Figure 2 Creating a free-form surface

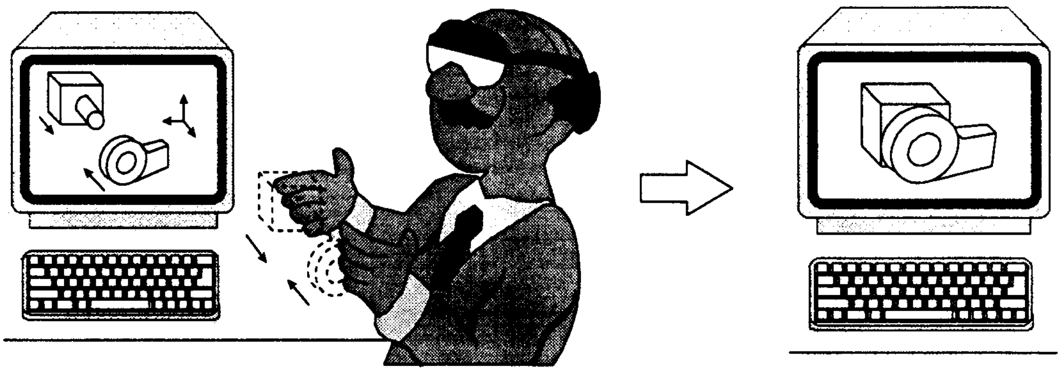


Figure 3 Creating an assembly

the computer to attach them to two of the closest surfaces on the parts or assemblies.

Part and assembly modification

Part/component modification implies, essentially, modifying its existing features. Feature modification implies changing its shape, dimensions, locations (transformation) or relationships with other features. Feature modification also implies deletion of features. These modification activities require the user to select the existing entities to modify them. (Entities include the dimensions, points, edges, surfaces and relationships on the features and the feature itself.)

For selecting an entity on a relatively simple geometry, the entity identification (ID) number or name can be graphically located on the entity so that a designer may call out its ID for selecting it. However, for a more complex geometry, the entity ID number or name may have to be hidden in order to reduce clutter in the environment. In this case, the user can identify the entity by pointing to it using her/his finger and performing certain gestures, or by gazing at the entity and then issuing a voice command like "select cube", "select surface", "select edge", etc. After an entity is selected, modification of its shape or dimensions can be done by using eye, hand motions or voice command. For example, to modify the depth of a blind hole, the user can select the depth dimension of the blind hole and issue a voice command like "change depth to 2 inches". This can also be done by pulling or pushing the blind hole to the desired depth by hand motion.

Modifying the location of a feature can be done by first detaching the feature from the part by issuing a voice command like "detach" or by performing a hand gesture to detach it, and moving it to the new location. Deleting features from the part can be done with a voice command like "delete". Specifying or modifying the relationship between features and the part involves selecting the entities and issuing voice commands to modify its relationship. For example, the designer specifies the distance between two blind holes to be constant (as shown in *Figure 4*) as a design constraint. After selecting both holes, she/he issues a voice command to set the constraint; therefore, if one hole is moved, the other automatically moves with it.

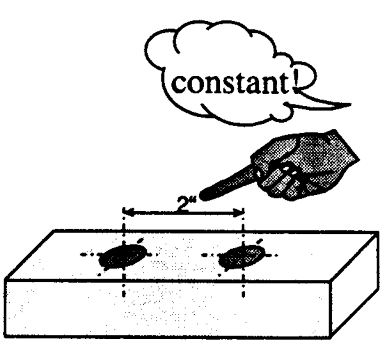


Figure 4 Specifying relationships between features

Assembly modification involves changing the configurations of an assembly. This includes activities such as selecting parts from the assembly, detaching parts from the assembly, and then deleting the part or reattaching the part to the new location of the assembly or modifying relationships between parts. These activities can also be done in a manner similar to modifying features on a part in the virtual environment.

It is also important to note that, whenever the user is creating or modifying an assembly, one must often resort to redesigning an individual part or to designing a new part. Therefore, in an abstract sense, part generation and modification can be considered as subsets of assembly generation and modification.

Design review

Reviewing a design involves the designer accessing some aspects of the part and assembly design. In design review, no changes are made to the design of a product. The two essential components in design review are: (1) selecting a feature, part or assembly and (2) querying the feature, part or assembly. Again, selection may be done in the same manner as described in the previous sections. Querying involves requesting information about a certain aspect of the design. For example, a query can be used to determine the location of a feature on a part. This information could be obtained by issuing a voice command input such as "location" followed by a sound output from the computer such as "the location of the feature is $x = 2.0$, $y = 1.0$, and $z = 0.0$". Another output mechanism for design review is graphic/visual output, which is more effective if one wants to query the geometrical shape of a complex part or assembly. Another example of a query is to examine the relationship between two parts. For example, a user may query the relationship of a slot to any other feature on the part. She/he may issue a verbal command referring to

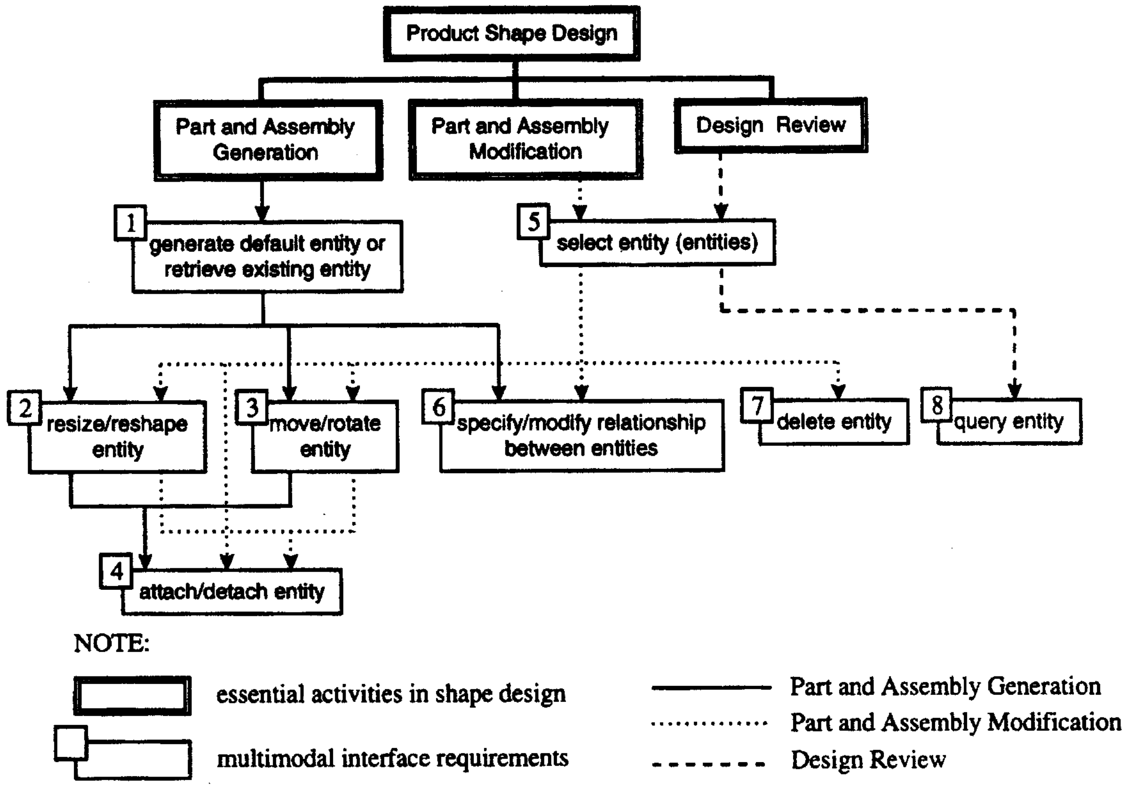


Figure 5 Multi-sensory interface requirements

the slot or by pointing to the slot; then requesting information about all relationships pertaining to the slot.

Multi-sensory interface requirements

On the basis of the above discussion, the requirements for the multi-sensory interface for product shape design are determined in this section. Product shape design is divided into three essential activities: (1) Part and Assembly Generation, (2) Part and Assembly Modification and (3) Design Review. These activities are shown in the double-lined boxes in *Figure 5*. The requirements for our multi-sensory interface for product shape design are determined by investigating the operations in each of these three activities. The multi-sensory interface requirements for these activities are presented in the single-lined and numbered boxes pointed to by solid, dotted and dashed arrow lines in *Figure 5*.

As mentioned in the earlier sections, *part and assembly generation* can be done by first generating default parts or features or by retrieving existing parts which are created by the designer and stored in the system database. Then, the designer sets the sizes, shapes, locations and orientations of the parts or assemblies and finally attaches them together. Therefore, the requirements for part and assembly generation are determined as: (1) generate default entity or retrieve existing entity, (2) resize/reshape entity, (3) move/rotate entity, (4) attach/detach entity, and (6) specify/modify relationship between entities. These numbered requirements can also be identified in the numbered boxes by following the solid arrow lines in *Figure 5*. (For convenience, here and throughout the rest of the paper, 'entity' or 'entities' may represent one or more of the following items: parametric dimension, relationship, point, edge, surface, feature, part and assembly.)

For *part and assembly modification*, entity selection is the first design step. Then, the user can resize/reshape, move/rotate, attach/detach or delete an entity, or specify/modify relationships between different entities. So, the requirements for product modification are determined as (numbering for all requirements as shown in *Figure 5*): (5) select entity or entities, (2) resize/reshape entity, (3) move/rotate entity, (4) attach/detach entity, (6) specify/modify relationship between entities, and (7) delete entity. These requirements can also be identified in the numbered boxes by following the dotted arrow lines in *Figure 5*.

For *design review*, the designer also needs to select the entity first and then she/he can perform a query on the selected entity. So, the requirements for product review are determined as: (5) select entity or entities, and (8) query entity. These requirements can also be identified in the numbered boxes by following the dashed arrow lines in *Figure 5*.

By formulating the activities in product shape design, the requirements for the multi-sensory interface of product shape design are determined as the eight numbered boxes shown in *Figure 5*: (1) generate default entity or retrieve existing entity, (2) resize/reshape entity, (3) move/rotate entity, (4) attach/detach entity, (5) select entity or entities, (6) specify/modify relationship between entities, (7) delete entity, and (8) query entity. The sensory interaction mechanisms are evaluated with respect to these requirements.

SENSORY INTERACTION MECHANISM

VR devices

An important issue when creating the VR-based CAD system is the availability of devices that can support the interface interaction mentioned above. The field of VR-related devices is changing very rapidly. Prior to the discussion of the sensory interaction mechanism, we shall briefly discuss a host of the state-of-the-art VR devices.

Input devices

Voice command. Voice input provides a convenient way for the user to interact with the virtual environment by freeing her/his hands for use with other input devices. Voice recognition technology has evolved to the point where voice recognition software can be bought off the shelf; however, it is still not robust. Examples of such softwares are VoiceAssist™ from SoundBlaster, IN^3™ Voice from Command Corp. Inc., and DragonDictate™ from Dragon System Inc.

Eye movement. The input devices that can be used to detect eye movements are biocontrollers. Biocontrollers can process indirect activities, such as muscle movements, and produce electrical signals. For example, dermal electrodes placed near the eye can detect eye muscle activities and allow one to navigate through the virtual worlds by moving one's eyes. Such devices are still in the testing and development stage.

Hand gesture and motions. The input devices for capturing a designer's hand gesture and motions can be divided into three categories: tracking devices, point input devices, and glove type devices. Tracking devices are used in tracking the user's hand and/or head position and orientation. Tracking sensors based on mechanical, ultrasonic, magnetic and optical systems are available. One example of such a device is Flock of Birds™ from Ascension Technology Corp. Point input devices include the six degree-of-freedom (d.o.f.) mouse and force ball. The six d.o.f. mouse functions like a normal mouse on the desktop but as a six d.o.f. once lifted from the desktop. An example of such a device is the Flying Mouse™ from Logitech. A force ball uses mechanical strains developed to measure the forces and torques the user applies in each of the possible directions. An example of such a device is the Space Ball™ from Space Ball Technology Inc. Glove type devices consist of a wired cloth glove that is worn over the hand like a normal glove. Fiber-optical, electrical or resistive sensors are used to measure the position of the joints in the finger. The glove is used as a gesture input in the virtual environment. Examples of such gloves are 5-th Glove™ from Fifth Dimension Technologies Inc. and CyberGlove™from Virtual Technologies Inc.

Output devices

Auditory output. Auditory output has the advantage of being a channel of communication that can be processed in parallel with visual information. 3D sound, in which the different sounds would appear to come from separate locations, can be used to provide a more realistic VR experience. Most workstations and PCs are equipped with sound cards and can provide the 3D sound effects. One example of the 3D auditory output is Alphatron™ from Crystal River Engineering.

Visual output. Two types of technologies are available for 3D visual feedback. The first is the head-mounted display (HMD). This typically uses two liquid crystal display (LCD) screens to show independent views for each eye. Examples of HMD are Virtual-I/O i-glasses™ and MRG2™ from Liquid Image Corp., VR4™ from Virtual Research System, and General Reality's CyberEyex™. The second method uses a stereo image display monitor and LCD shutter glasses. In this system, two images (as seen by each eye) of the virtual scene are shown alternately at a very high rate on the monitor to create a stereoscopic image. An example of such a device is the StereoGraphics' CrystalEyes™.

Tactile output. This type of feedback device allows a user to feel the forces, touch and resistance of objects in the virtual environment. One method of simulating different textures for tactile feedback is to use electrical signals or vibrations at the different points on the hand. An example of this device is CyberTouch™ tactile feedback system from Virtual Technologies Inc. Another approach is to use inflatable pockets in a glove to provide touch feedback. For force feedback, some mechanical devices (arms) are used to provide resistance as the user tries to manipulate objects in the virtual environment. Examples of such devices are Phantom™ force-reflecting haptic interface from Sensible Devices Inc. and SAFIRE™ from EXOS Inc.

Sensory interaction

The present research reduces the interface of the virtual environment to three sensory interaction mechanisms: tactile, visual and auditory. For each of these mechanisms, two separate modes exist: input and output. Input refers to the information fed into the virtual environment by the user through hand motion/gestures, voice commands and eye movements. Output refers to the sensory feedback in the virtual environment according to a specific input.

An example of the input mode is the generation of a free-form surface of a part by hand motions. The input mode here involves the tactile interaction mechanism—tracking the hand motions. Once the surface of a part is created, the designer uses his/her hands to feel it. The feel of the surface (the tactile output from the computer) is the output mode for the tactile interaction.

For the visual interaction mechanism, there is an input mode in which the human controls the environment by eye motions. Visual input could allow the selection of an object. For example, the user may look at a component in the model of a virtual automotive engine to select it and then use another input mechanism such as voice or hand input to move it. Movement of an object by eye motion could be a rather difficult task owing, in particular, to the lack of reliable devices. For visual output, the virtual environment allows the designer to see the design in a stereoscopic mode as it would look in reality.

The auditory input mode allows a user to talk to the virtual environment. The virtual environment 'hears' what the user is saying and takes actions accordingly. In the auditory output mode (output from the virtual environment) the virtual environment 'talks' to the user. Technologically, portions of this are feasible through voice recognition and computer-generated sound. There are six types of possible interactions—three for input: (i) visual input, (ii) auditory input, (iii) tactile input, and three for output:

Table 1 Results for single interaction mechanism

Requirements	Interaction modes						Average
	Input			Output			
	voice	eye	hand	auditory	visual	tactile	
Generate default entity or retrieve existing entity	8.4	1.9	6.8	4.3	9.1	3.9	5.8
Reshape/resize entity	6.8	2.3	8.6	3.5	9.7	5.2	6.0
Move/rotate entity	6.8	4.3	8.5	3.2	9.6	4.5	6.2
Delete entity	8.5	3.6	7.0	6.0	9.3	3.2	6.2
Select entity or entities	6.7	6.2	9.5	5.7	9.3	4.4	6.9
Query entity	8.4	4.2	6.7	7.1	9.0	3.4	6.5
Specify/modify relationship between entities	8.3	2.6	6.3	5.8	9.0	3.8	6.0
Attach/detach entities	8.4	3.3	7.8	6.2	8.9	4.5	6.5
Average	7.8	3.5	7.7	5.2	9.3	4.1	

(i) visual output, (ii) auditory output, (iii) tactile output. The research systematically assesses the interface requirements for the application of product shape design with respect to the combinations of these six variables in the virtual design environment.

INTERACTION MECHANISM ASSESSMENT

The interaction mechanisms developed in the present research need to be assessed and ranked in order of importance with respect to the requirements presented above. There are a total of seven possible combinations for visual, auditory and tactile interaction mechanisms: each of the three used independently (3 combinations), any two out of three used at a time (3 combinations), and all three used at the same time (1 combination). The first combination refers to a single interaction mechanism and the latter two combinations refer to the multiple interaction mechanisms. The usability and usefulness of the sensory input/output modes with respect to the requirements are determined on the basis of interviews with 21 industrial designers and CAD users. All the interviewed individuals are experienced CAD users and are proficient in using AutoCad™ or Pro/ENGINEER™ or some other solid modeler. An introduction to the VR-CAD system and the interaction mechanisms were presented to the designers prior to the interview. All the sensory interface devices were introduced to the designers.

The evaluation results for a single interaction mechanism are presented in *Table 1* and for multiple interaction mechanisms in *Table 2*. The first rows of both tables list the possible combinations of interaction modes. The first columns in both tables list the eight requirements identified in the earlier sections. The CAD users were asked to give a rating (on a scale of 1 to 10) of each interaction mode on the first row for achieving the corresponding requirement on the first column. The last columns of both tables are the total average for the corresponding requirements listed in the first column. The last rows of both tables are the total average for the corresponding interaction modes listed in the first row.

In *Table 1*, the total averages for input voice command (7.8) and hand motion/gesture (7.7) are similar and are both much higher than eye motions (3.5) in the single input mechanism. These averages indicate that most users would prefer to use voice command or hand motion/gesture as the main input methods. However, the eye motion rating in the single input mechanism for selecting an entity is as high as 6.2, which is quite close to the rating for the voice command (6.7) and the highest rating for eye motion input mode. This suggests that some users consider eye motion to be useful in entity selection. The ratings for achieving reshape/resize and move/rotate entity, which are directly related to the shape and position of the entity, indicate that most users consider hand motion and gesture to be more useful than the voice command.

In the single output mechanism, the total average for visual output (9.3) is higher than that for auditory (5.2) and tactile output (4.1). This implies that the visual output

Table 2 Results for multiple interaction mechanism

Requirements	Interaction modes								Average
	Input				Output				
	voice & eye	voice & hand	eye & hand	voice, hand & eye	auditory & visual	auditory & tactile	visual & tactile	auditory, tactile & visual	
Generate default entity or retrieve existing entity	6.6	8.5	6.0	8.8	8.3	4.6	8.0	9.4	7.5
Reshape/resize entity	5.1	8.5	7.7	9.0	8.3	4.3	8.4	9.6	7.6
Move/rotate entity	6.6	8.6	7.9	9.4	8.2	4.0	8.5	9.6	7.9
Delete entity	6.9	9.0	6.6	9.2	8.4	5.6	7.7	9.1	7.9
Select entity or entities	7.4	8.3	8.6	9.2	8.0	5.7	7.6	9.6	8.1
Query entity	6.8	8.8	7.7	8.8	9.0	5.8	7.0	9.4	8.0
Specify/modify relationship between entities	7.4	8.5	6.0	9.0	9.0	5.5	7.9	9.6	7.8
Attach/detach entities	7.0	9.0	6.9	8.7	9.0	6.3	7.8	9.6	8.0
Average	6.7	8.7	7.2	9.0	8.5	5.2	7.9	9.5	

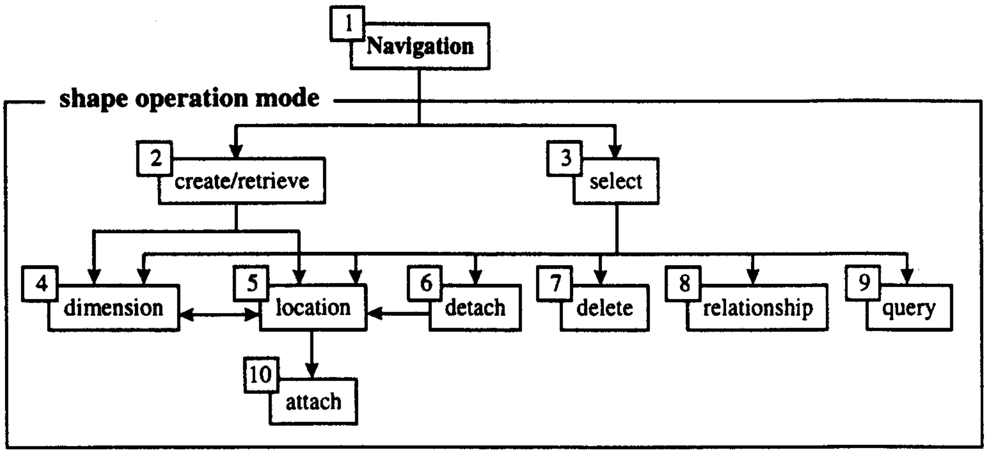


Figure 6 VR-CAD system architecture

is the most important output mechanism for shape design in the virtual environment. The highest rating for auditory output is 'query entity' (7.1). The users consider the sound output to be a viable feedback mechanism when querying the information pertaining to an entity. The highest rating for tactile output is 'reshape/resize entity' (5.2) and indicates that the tactile feedback is somewhat helpful in reshaping or resizing the entity. (As mentioned earlier in this paper, it is helpful for the user to have tactile feedback when she/he is creating or modifying a free-form surface, which is a sub-activity in 'reshape/resize entity'.)

The total average ratings for each requirements are mainly averaged around 5 to 6. This indicates that a single interaction mechanism can only provide 50% to 60% usefulness and helpfulness in achieving these requirements and is not a completely satisfactory interaction mechanism for product shape design in the virtual environment. To solve this problem, a multiple input and output interaction mechanism may be used.

In the multiple input mechanism (*Table 2*), the rating for combining voice command, hand motion/gesture and eye motion (9.0), i.e. all three input modes, is the highest among all combinations. However, if eye motion is not provided to the user, the total rating is still as high as 8.7. This indicates that, even without eye motion, the voice command and hand motion/gesture probably will suffice for achieving the requirements. In addition, there is still a lack of reliable devices for tracking the eye motions; therefore implementing eye-based control is considered not to be feasible in the current stage. The lowest rating for combining voice command and hand motion/gesture is 'select entity or entities' (8.3). This indicates that the designer might encounter difficulties in selecting an entity or entities. However, the rating is still relatively high on a scale of 0 to 10. In the current research, voice command and hand motion/gesture will be used as the input mechanism for the VR-CAD system.

In the multiple output mechanism, the total points for combined auditory, tactile and visual output (9.5) are the highest among all combinations. The total points for any combination with the presence of visual output are also high (auditory and visual: 8.5 and visual and tactile: 7.9). Auditory and visual are being used as the output mechanisms for the current VR-CAD system owing to a lack of reliable devices for tactile feedback. The average rating for achieving requirements by multiple interaction modes are generally around 8 and indicates that the user can acquire 80% of usefulness and helpfulness by multiple interaction mechanisms.

INTERFACE DEFINITION FOR VR-CAD SYSTEM

On the basis of the investigation into the requirements for the multi-sensory interface and the interaction mechanism, the interface definition for a VR-CAD system are determined in this section. There are two essential modes in the VR-CAD system: navigation mode and shape operation mode. The first mode, navigation mode, provides the product designer the ability to navigate through the design space to view the generated geometric shapes. The designer may use hand or eye motions and voice commands for navigation. Real-time 3D images, auditory and tactile feedback may be provided to the designer for human-like interactions in the virtual environment. The second mode, shape operation mode, provides the designer the ability to use hand or eye motions and voice commands to create or modify the geometric shapes with the visual, auditory and tactile feedback in the virtual environment. The designer switches between these two modes to generate the geometric shapes of the product design. While the discussion considers eye-based input as well as tactile-based output, in our implementation these are not utilized (as will be discussed later). However, our approach does not exclude them in theory.

The architecture of the interface is based on a network of nodes that defines user activities. The user can be performing any activity which is represented by a node in the network. Since a given activity can be preceded and followed only by selected activities, the network forms a natural data structure to represent this relationship. The network contains directed arcs that allow the precedence relationships to be stored. A preliminary analysis suggests that the following 10 nodes (i.e. 10 activity classes) are the most relevant ones for navigation and shape operation modes: (1) navigation, (2) create/retrieve, (3) select, (4) dimension, (5) location, (6) detach, (7) delete, (8) relationship, (9) query, and (10) attach, as shown in *Figure 6*. The designer may travel around these nodes by issuing voice commands to create shapes. For example, the create object activity (node 2) must be followed by either dimension (node 4) or location (node 5) activities. The way in

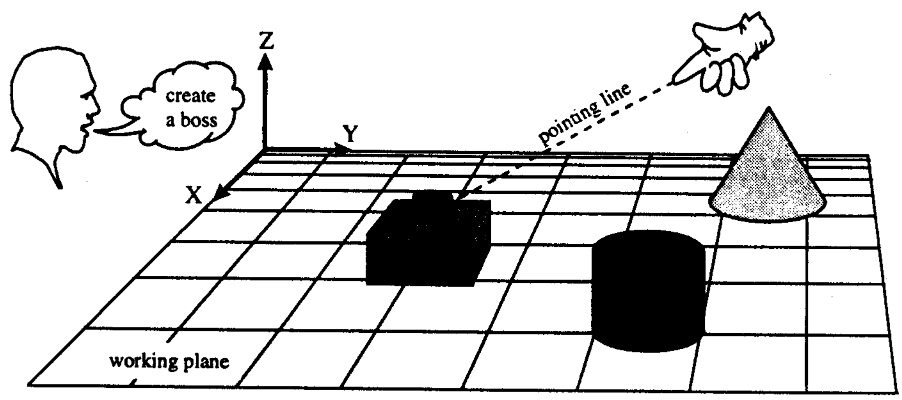


Figure 7 Design space

which the interaction mechanism has been defined with respect to the network of nodes is discussed in the following sections.

Design space

The working environment for the product shape designer in the current VR-CAD system is called the 'design space', as shown in *Figure 7*. The designer creates parts or components on the working plane by using hand motions/ gestures, voice commands and eye motions. A 'pointing line' is attached to the index finger of the user's hand image in the virtual environment to assist the user to indicate the desired location for design operations. The user navigates through the design space by 'grasping' the entire design space with the purpose of translating or rotating the viewpoint of the design space. The user also zooms in or zooms out of the scene by issuing voice commands.

Although there are three input modes (voice command, hand motion/gesture, eye motion) for the designer to perform design operations, voice commands are considered to have the highest priority over the other two input modes. This is because voice commands can reveal the designer's intentions more efficiently and directly to the VR-CAD system. An example of the situation where voice commands have a higher priority is when a designer issues a voice command "height 5 inches" while he/she is dragging the size of a cube by using his/her hand motions: the VR-CAD system responds to he voice command and sets the height of the cube to 5 inches. In this case, any hand motion inputs that intend to change the height of the cube are ignored by the VR-CAD system.

Node traveling

There are two entry nodes for the designer to access the shape operation mode: (i) create default entity or retrieve existing entity and (ii) select entity. Three voice commands are usable to enter these two nodes: "*create*", "*retrieve*", or "*select*". After entering the shape operation mode, the following voice commands may be used to travel around the nodes in this mode: "*dimension*", "*location*", "*detach*", "*relationship*", "*delete*", "*query*", and "*attach*". The designer can, at any step, issue a voice command, "*undo*", to travel back to the previous node and discard the changes made in the current node.

From all nodes, except the detach node, the user can travel directly back to the navigation mode without having to travel through any other nodes. (The reason why the user cannot travel back to the navigation mode directly from the detach node in the shape operation mode is because, after detaching an entity, the user must relocate the entity in the design space.) One way by which the designer can switch back to the navigation mode from the shape operation mode is by a voice command: "*done*". Since system default values exist for the dimension and location, the designer need not explicitly specify

Table 3 Input/output interaction mechanism for each node

Nodes	Modes					
	Input			Output		
	hand	voice	eye	visual	auditory	tactile
Navigation	P	P	S	P	S	S
Create/retrieve	P	P	–	P	S	–
Select	P	P	S	P	S	S
Dimension	P	P	–	P	–	–
Location	P	P	S	P	S	S
Detach	P	P	–	P	P	S
Delete	–	P	–	P	P	S
Relationship	–	P	–	P	S	–
Query	–	P	–	P	P	–
Attach	P	P	–	P	P	S

P: primary interaction modes
S: secondary interaction modes
–: interaction modes not provided

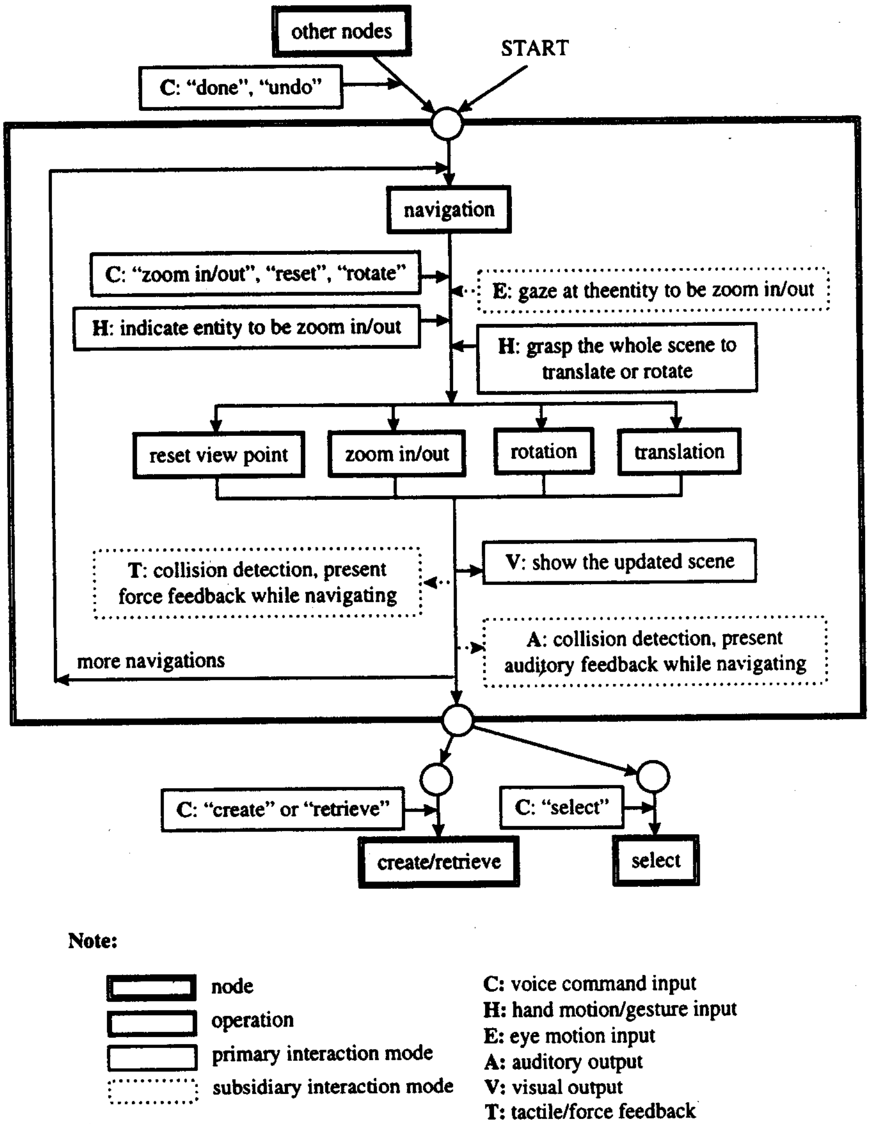


Figure 8 Navigation node

all the dimensions and locations of the shape before exiting the shape operation mode. This provides the designer with a more friendly and convenient way of creating shape designs.

Node interface interaction mechanism

The functionality in each node on the interaction graph, as shown in *Figure 6*, is provided with different combinations of interaction mechanisms. *Table 3* converts the numerical values for the input/output mechanism as discussed earlier into a subjective interaction mechanism of the current VR-CAD system. The first column in *Table 3* lists the nodes in the current VR-CAD system and the first row lists all the possible interaction modes. In this table, a 'P' indicates the primary interaction modes that are used in the node listed in the first column. An 'S' indicates the secondary interaction modes and a dash, '–', indicates a mode that is not provided to the designer. For example, in the navigation mode, hand motion and voice commands are used as the primary input mechanism for navigating through the design space while visual images are used to provide the designer the primary feedback from the design environment. In addition, eye motion input, auditory and tactile feedback output may also be provided to the navigation mode as the secondary input and output mechanism to the designer. The secondary modes are not as important as the primary modes in performing the functions in the node but provide the designer an optional input mechanism or helpful output feedback.

Navigation

When the VR-CAD system is started, the default mode is the navigation mode. Since there is only one node in this mode, i.e. the navigation node, the user may perform the operation in this node. The user may also enter this node by issuing voice commands such as ''*done*'' or ''*undo*'' while he/she is in the shape operation mode. *Figure 8* shows the potential operations and the interface interaction mechanisms for this node. (In *Figures 8–20*, the double-lined boxes represent each node in the current system; bold single-lined boxes represent the operations in each node; solid or dashed single-lined boxes with capital letters, such as C, H, E, A, V, T, represent voice Command, Hand motion/gesture, Eye motion inputs,

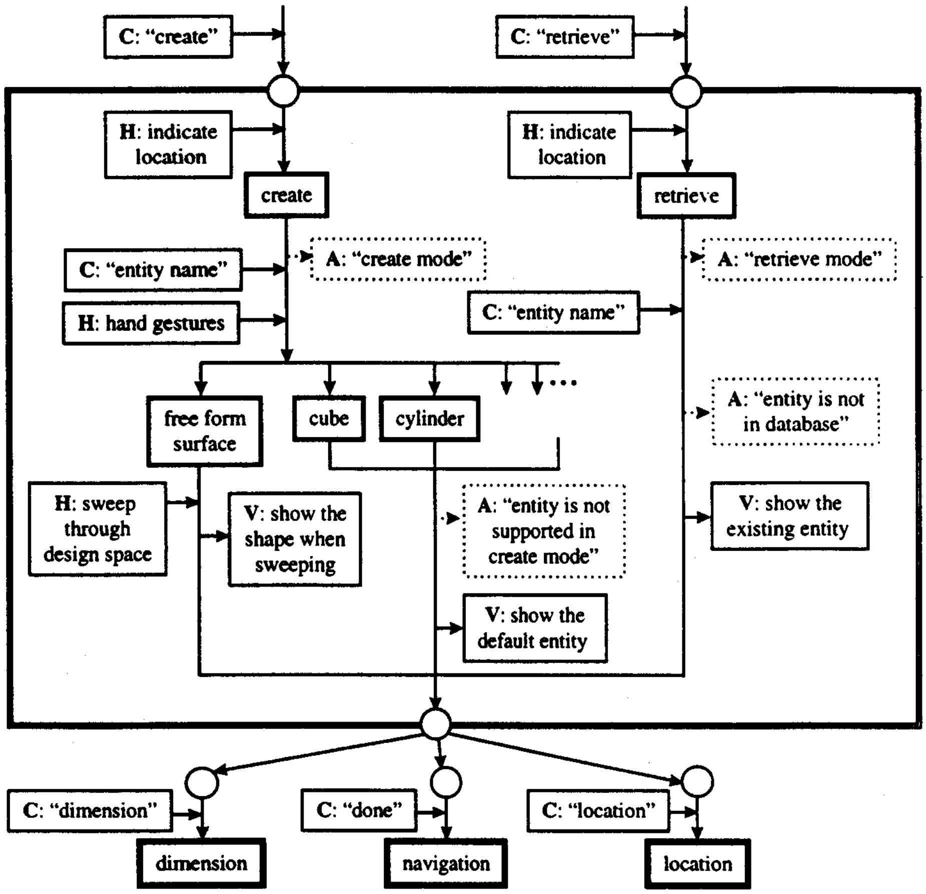


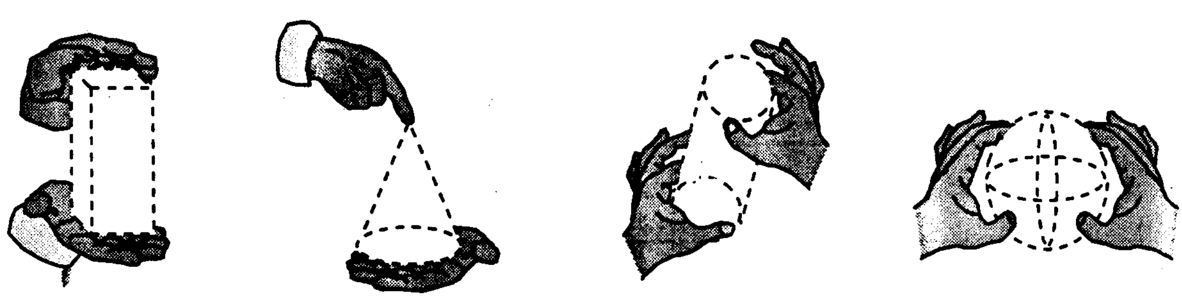
Figure 9 Create/retrieve node

Auditory, Visual and Tactile outputs, respectively. Solid single-lined boxes represent the primary interaction modes. Dashed single-lined boxes represent subsidiary interaction modes.)

As shown in *Figure 8*, when the designer enters the navigation node, he/she may issue voice commands such as ''zoom in'', ''zoom out'', ''reset'' and ''rotate'' to zoom in/out, reset, or rotate the scene of the design space. The user may also use eye motions and finger positions to indicate which entity to zoom in/out. He/she may also use hand gestures to 'grasp' all the entities in the scene to perform rotation or translation operations. While the designer is navigating the design space, visual output shows the updated 3D images, auditory output and tactile output present auditory and force feedback if there is a collision between the virtual hand and virtual entities in the design space. The designer may repeatedly perform navigation operations in this node until he/she issues a voice command, ''create'', ''retrieve'' or ''select'', to enter other nodes in the shape operation mode.

Create/retrieve

The main functions in this node are: (i) creating an entity with the default size and (ii) retrieving an existing entity. There are two voice commands that can be used to enter this node: ''*create*'' or ''*retrieve*''. As shown in *Figure 9*, the designer may use the index finger position to indicate the location for the entity that is being created or retrieved while the user issues the voice commands. After the designer enters the ''create/retrieve'' node, the VR-CAD system is ready for the user to create or retrieve an entity. Auditory feedback can also indicate that the user is currently in the create or retrieve mode.



(a) create a cube (b) create a cone (c) create a cylinder (d) create a sphere

Figure 10 Hand gestures for creating entities

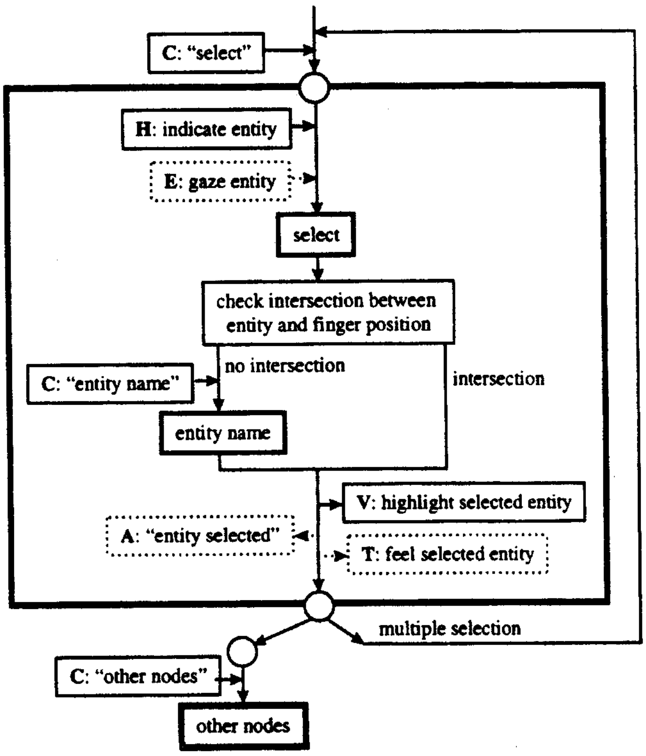


Figure 11 Select node

There are two primary input modes for creating an entity in the design space: hand gesture or voice command. (These primary input modes are based on *Table 3*.) The designer may use hand gestures to create an entity such as a cube, cylinder, cone or sphere as shown in *Figures 10(a)–(d)*. The designer may also issue a voice command such as "cube", "cylinder", "cone", "sphere", "boss", "blind hole", etc., to create or retrieve the entity. If the designer issues a voice command for an entity name that is not currently supported in create mode or does not exist in the database in the retrieve mode, auditory output may be used to provide an error message. If the designer is creating a free-form surface, he/she may use hand motion to 'sweep' through the design space to create the free-form surface. The visual output shows the created or retrieved entity with the default dimensions. Once the entity is created or retrieved, the designer can issue a voice command "done" to go back to navigation node, "dimension" to go to dimension node, or "location" to go to location node.

Select

The main function in the select node is to select an entity from the design space to make shape changes to the entity. As shown in *Figure 11*, the designer can use his/her hand (probably an index finger on the hand) to indicate the entities to be selected. The VR-CAD system will check if the designer has indicated the entity to be selected by his/her finger and highlight the selected entity through the visual output. Auditory and tactile output may also inform the designer about the selected entity through voice and tactile feedback.

Instead of using touch input for selection, a voice command that calls out the entity name may be used to select the entity. The designer may select more than one entity in the design space by issuing a voice command, "select", repeatedly. He/she may also go to the other

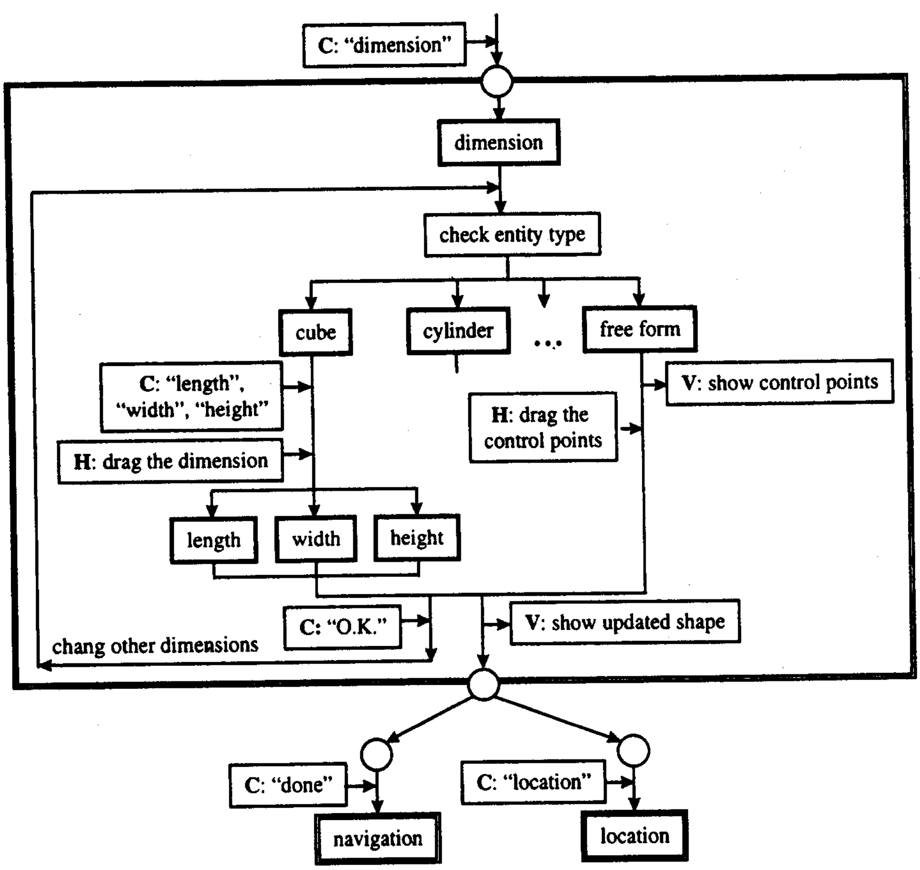


Figure 12 Dimension node

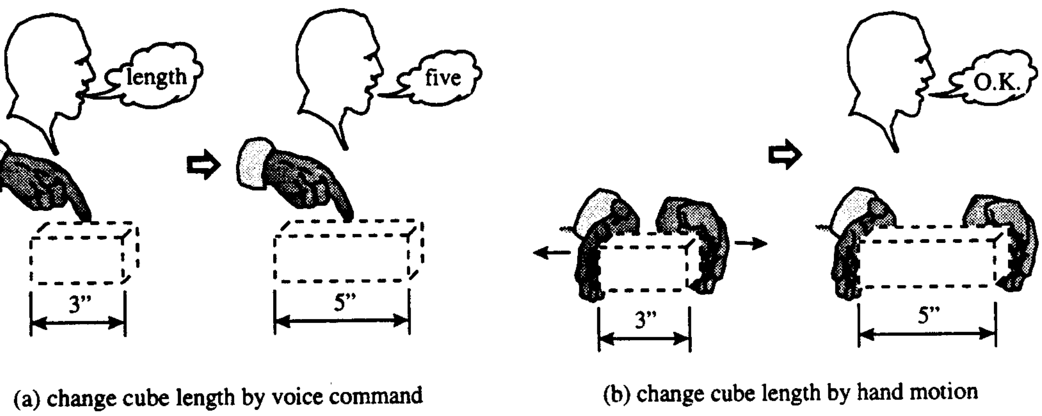


Figure 13 Change the dimension of a cube

nodes to make design operations on the selected entity by issuing voice commands for other nodes.

Dimension

The primary operation in the dimension node is the resizing or the reshaping of the selected entities. The design operations in this node are entity-based, i.e. the operations a user may perform in the dimension node depend on the type of entity being modified. For example, to change the dimensions of a cube, the designer is allowed to modify the length, width or height of the cube. On the other hand, the dimensions of a cylinder that are editable are the diameter and height.

As shown in *Figure 12*, after entering the dimension node, the operations provided depend on the type of the entity edited. As assessed by *Table 3*, the designer is allowed to use voice commands or hand motions to change the dimensions of the selected entity. For example, to change the dimension of a cube, the designer may issue two voice commands, ''length'' and ''5'' (as shown in *Figure 13(a)*). He/she may also use hand motions to drag the size of the cube and issue the voice command ''OK'' once the desired size is reached (as shown in *Figure 13(b)*). Changing the dimensions of a free-form surface is different from changing the dimensions of other shapes. When changing the dimension of a free-form surface, the control points of the surface are displayed in the design space to allow the user to drag these control points to change its shapes. Visual output is used to show the updated shape of the entity that is being resized or reshaped. To leave the dimension node, two voice commands, ''one'' and ''location'', are used. The former transfers the user to the navigation node and the latter to the location node.

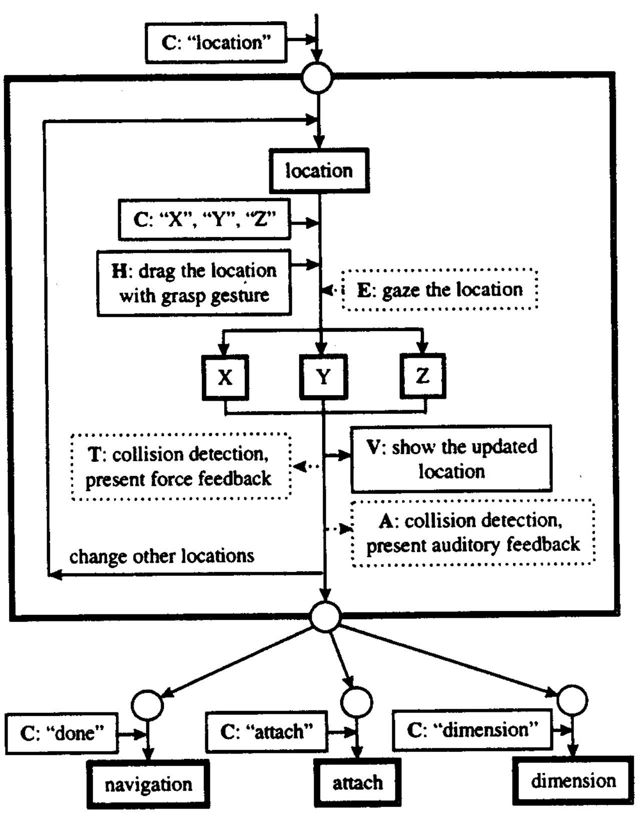


Figure 14 Location node

Location

The main functions in the location node are: (1) change the position of the entity and (2) change the orientation of the entity. As shown in *Figure 14*, the designer may issue voice commands like ''X'', ''5'', ''Y'', ''10'', ''Z'' and ''15'', to move the entity to x = 5, y = 10 and z = 15. The designer may also grasp the entity in the design space and translate or rotate the entity to the desired position and orientation. Eye motion may also be used to locate the entity position. The designer can gaze at a certain location in the design space and move the entity to this position. (This is not implemented in the current VR-CAD system but is possible for future research.) Visual output displays the updated position and orientation of the entity in the design space. Auditory and tactile output present the auditory and tactile feedback if there is a collision between the moving entity and other entities in the design space. (Tactile output in not implemented in the current VR-CAD system.)

Three voice commands are used to exit the location node: ''done'', ''attach'' and ''dimension''. They are used to travel to the navigation, attach and dimension node, respectively.

Detach

When the detach node is activated by a voice command, ''detach'', the selected shape is detached from the rest of the entity and the active node moves to the location node so that the designer can relocate the position of the selected entity. (The detach command is used only if an

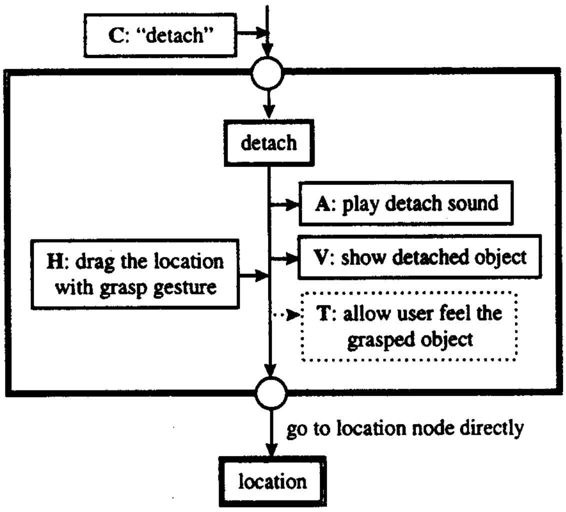


Figure 15 Detach node

entity is to be relocated to another location. For deletion of an entity, a "*delete*" command will be discussed next.) Once the "*detach*" command is completed, the location node becomes the default active node automatically—the user does not need to issue the "location" command again.

When the designer issues a voice command, "detach", he/she may use hand gestures to grab the detached entity and hold it in his/her hand. As shown in *Figure 15*, visual feedback updates the scene of the design space, auditory feedback plays the sound of detaching, and tactile feedback allows the user to feel the grabbed entity.

Delete

The only input mode for the delete node is the voice command, "delete". When the designer issues "delete", the selected entity is deleted from the design space and the user can travel directly back to navigation node without issuing further commands. As shown in *Figure 16*, the visual feedback erases the selected entity, the auditory feedback plays the sound for deleting, and the tactile feedback makes the grabbing force feedback disappear if the user is grabbing he entity while he/she issues the "delete" command.

Relationship

The relationship node is used to specify or modify the

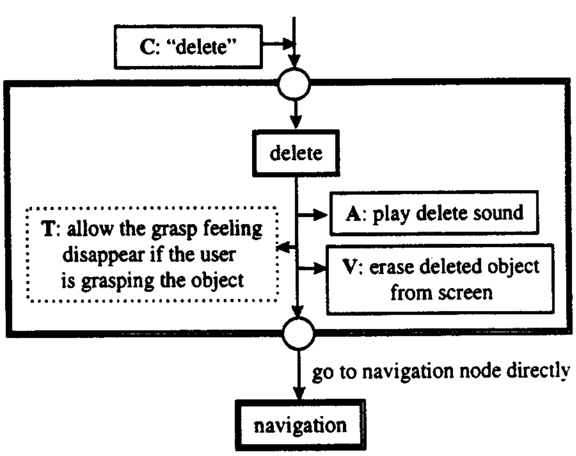


Figure 16 Delete node

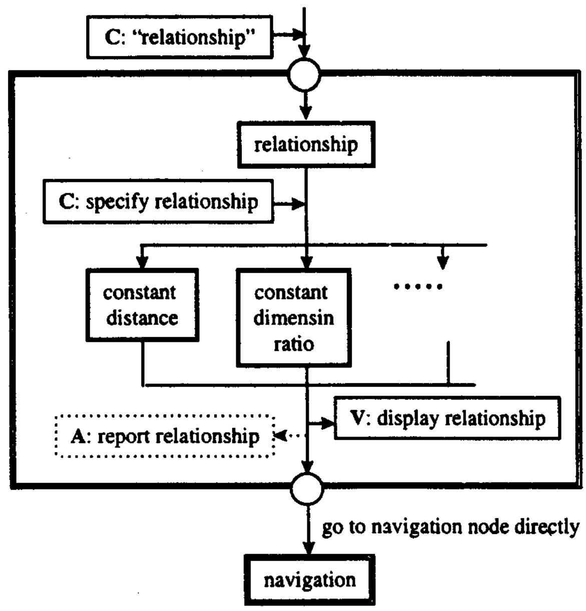


Figure 17 Relationship node

relationships between entities. Multiple selections of entities is allowed before entering this node. As shown in *Figure 17*, after entering the relationship node, voice commands such as "constant distance", "same size", "constant dimension ratio", etc., may be issued to specify or modify the relationship between entities (as shown in *Figure 18*). When a relationship is specified or modified, visual output may display the newly updated relationship, auditory output may also report this relationship, and the user can automatically travel back to navigation node.

Query

The main input mode in the query node is the voice command. As shown in *Figure 19*, the user may issue "dimension", "location" or "relationship" to query the corresponding information about the selected entity. Visual feedback displays the query results and auditory feedback is used to report the query results. After the

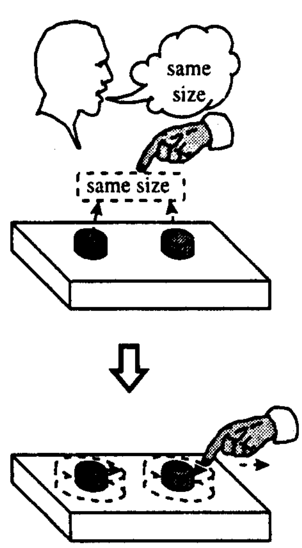


Figure 18 Set relationship

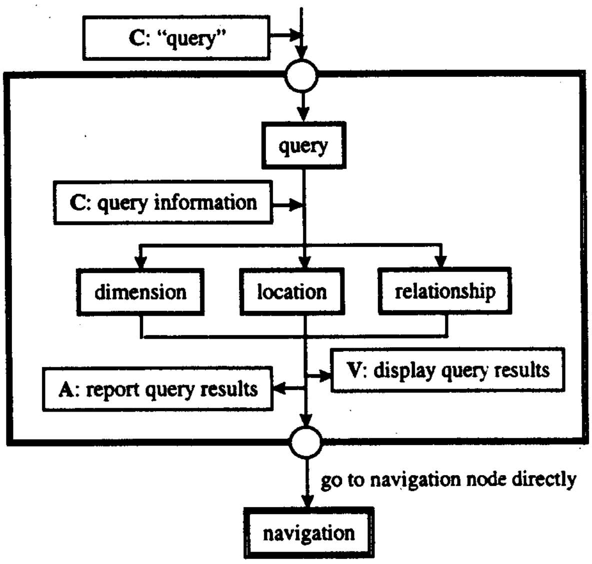


Figure 19 Attach node

results are presented, the user can directly return to the navigation node.

Attach

Before attaching an entity to some other entities, the designer needs to specify the location where the selected entity must be attached. Therefore, there is only one way to enter the attach node: entering from the location node by issuing the voice command ''attach''. As shown in *Figure 20*, the designer may ungrasp his/her hand to release the entity and attach it to the nearest surface of another entity while he/she issues the ''attach'' command. Visual feedback displays the attached entities, auditory feedback plays the sound of attaching, and tactile feedback makes the grabbing force feedback disappear. Again, the user returns directly to the navigation node after the attach operation is completed.

STATUS OF IMPLEMENTATION

Although we have discussed all the six modes of the

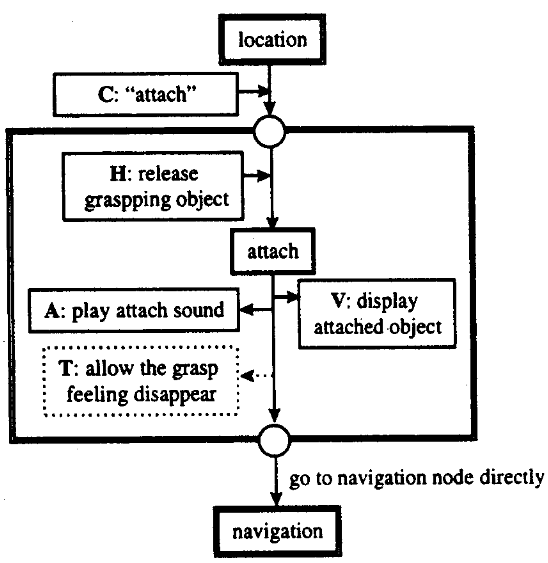


Figure 20 Attach node

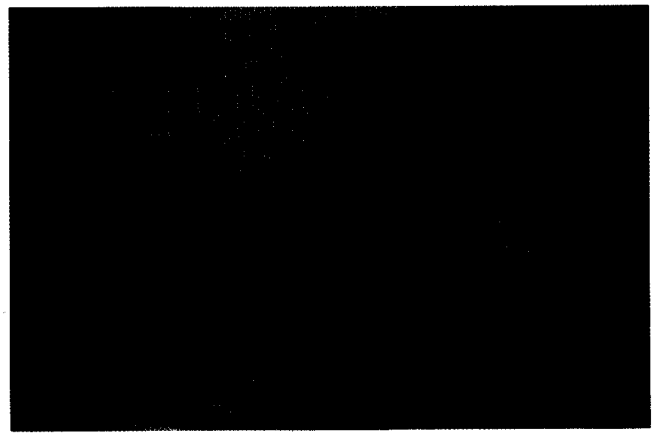


Figure 21 Current VR-CAD system

interaction mechanism, eye motion input and tactile output are not currently implemented in the VR-CAD system owing to the lack of reliable devices. However, voice command input, hand motion/gesture input, 3D visual output and auditory output have been successfully integrated into the current system. Portions of the proposed nodal network that define the interface interaction mechanism are still under development. The current implemented VR-CAD system allows the designer to issue voice commands to create some primitives such as cubes, cylinders, boss and ribs. The designer can also use his/her hand motions to manipulate the created entities in the design space. (Hand gestures input is still under development.) 3D images and auditory feedback are also implemented and provide the designer with a realistic interaction in the virtual environment. *Figure 21* shows the picture of the current VR-CAD system in this research.

The current VR-CAD is developed on the network-connected platforms of a Silicon Graphics™ Indigo^2 (SGI) and a Pentium Pro™ 200 PC. The auditory input and output are implemented on the PC platform through the IN-CUBE™ voice recognition program with the Sound-Blaster™ AWE-32 sound card. Visual output is implemented through the OpenGL™ library on the SCI machine. A pair of StereoGraphics CrystalEyes™ are used to provide the 3D images. Hand gesture and hand motion input are implemented through the 5th-Glove™ and the Ascension Flock of Birds™ six d.o.f. tracker with the Xtensory Xvs-SyncLink™ library. We have also developed the representation for attaching/detaching entities in the VR-CAD system[33]. *Figures 22(a)–(d)* show some of the parts created in the current VR-CAD system. These parts typically take two to five minutes to build in the current VR-CAD system. For example, the part shown in *Figure* 22d took the author under three minutes to create in the current VR-CAD system. Exactly the same part was also created in a traditional CAD system, Pro/ENGINEER™—in this case, in 26 minutes.

CONCLUSION

This paper investigates the multi-sensory user interface requirements for conceptual shape design and assesses the applicability of different input and output mechanisms in a virtual environment. The multi-sensory interface requirements are determined as the following eight items:

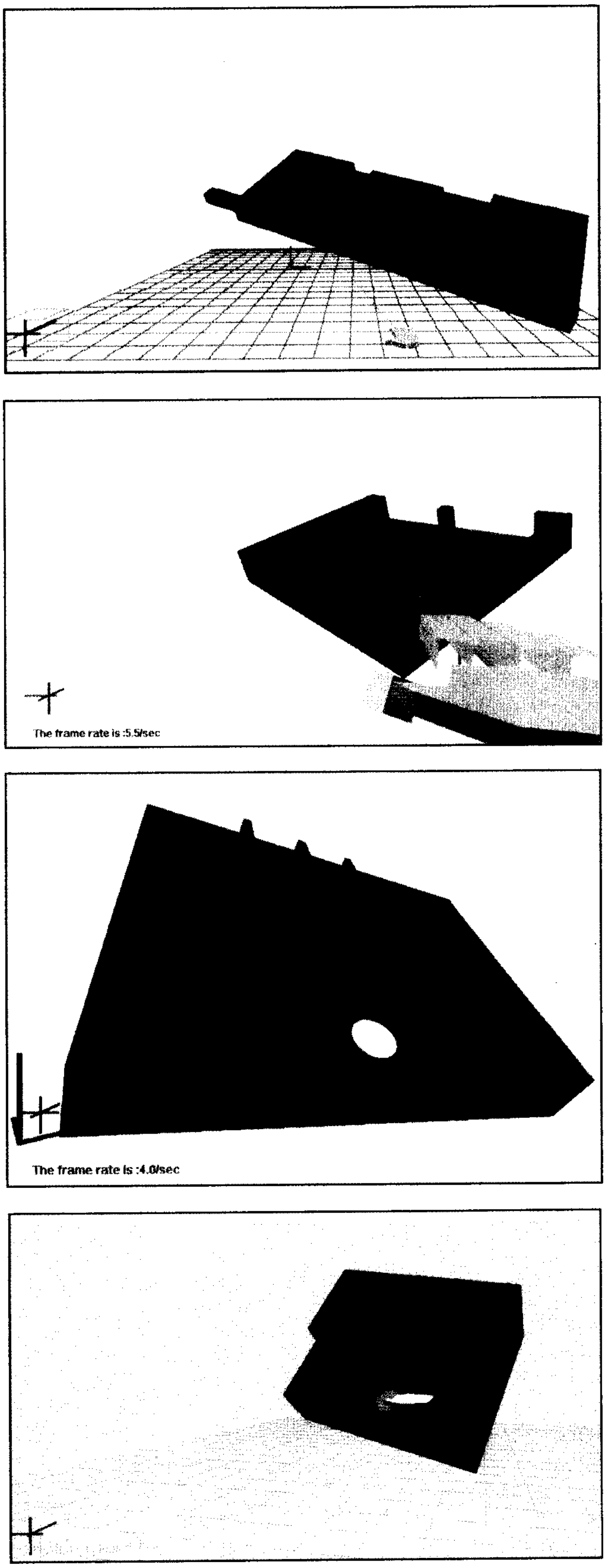


Figure 22 Some parts created in the current VR-CAD system

(1) generate default entity or retrieve existing entities, (2) resize/reshape entity, (3) move/rotate entity, (4) attach/detach entity, (5) select entity or entities, (6) specify/modify relationship between entities, (7) delete entity, and (8) query entity. A nodal network that defines the interface interaction mechanisms for the VR-CAD system is also proposed in the current research. At any stage, one node in the network is active, which indicates the activity class. Arcs between nodes represent the allowable transitions between activities. Voice command versus hand motion/gesture input mode and visual versus auditory output mode are used as the interaction mechanism in the VR-CAD system that we are developing.

Future work on the current research is to implement completely and test the proposed VR-CAD system for concept design in a virtual environment. The multi-sensory user interface requirements determined in the current paper will be verified and refined according to new research issues that may rise from using the system that we are developing. Eye motion input and tactile/force feedback will be integrated into the VR-CAD system once the technologies are developed to a reliable and mature stage. Other potential interaction modalities for the human–computer communication will also be investigated. The objective of the research is aimed at providing the product designer a more natural and intuitive communication with the CAD system.

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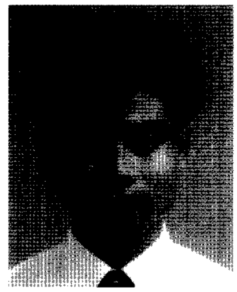

Chi-Peng P Chu is currently a PhD candidate in the Department of Mechanical Engineering at the University of Wisconsin–Madison. He received his BS from National Taiwan University, Taiwan, in 1990 and MS from University of Wisconsin–Madison in 1995. His research interests include virtual-reality-based CAD systems, and multimodal interface interaction in the virtual environment.

Rajit Gadh is currently an Assistant Professor of Mechanical Engineering at the University of Wisconsin–Madison. He obtained his BS in Mechanical Engineering from the Indian Institute of Technology in Kanpur. He has an MS in Mechanical Engineering from Cornell University and a PhD in Mechanical Engineering from Carnegie Mellon University. He has worked in the industry for about four years, for companies such as Ford Motor Company, General Motors and Digital Equipment Corporation. He also spent a year as a Visiting Faculty at the University of California–Berkeley. He is the recipient of several awards, including the SAE Ralph R Teetor Award and the prestigious National Science Foundation Early Faculty CAREER award.

Tushar H. Dani is currently a PhD candidate in the Department of Mechanical Engineering at the University of Wisconsin–Madison. He received his BS degree from the India Institute of Technology in Bombay in 1991 and MS from the University of Toledo, USA, in 1993. His research interests focus on the design and implementation of a computer system architecture for mechanical design, within a virtual environment.