Combining Physical and Semantical Navigation in Three-Dimensional Information Visualization

Cristina Russo dos Santos, Pascal Gros, and Pierre Abel

Institut Eurécom, 2229 Route des Crêtes, 06904 Sophia Antipolis, France

ABSTRACT

The field of information visualization is in permanent expansion and new and innovative ways of visualizing large volumes of abstract data are being developed. The use of virtual metaphoric worlds is one of them, but these visualizations per se are only truly useful if the user is provided a means of exploring the information. A common way of data exploration is navigation. In the case of three-dimensional (3D) information visualization, navigation as a means of information exploration attains even more importance due to the extra exploitable dimension. Nonetheless, navigation in large virtual worlds is still a difficult task and not only for naïve users; there is anecdotal evidence that electronic navigation is considered difficult even by the virtual worlds builders. Wayfinding, "knowing where to go", is sometimes perceived as the hardest part; other times, it is the locomotion, "getting there", that is found difficult. This paper presents a navigation strategy that attempts to solve these problems by combining physical/metaphoric navigation with semantic navigation. We present a framework for navigating large virtual worlds that relies heavily on the use of visual metaphors. The combination of physical and semantic navigation embedded in the metaphor components allows for a powerful data exploration and electronic navigation mechanism.

Keywords: Navigation, 3D Information Visualization, Visual Metaphors, Semantical navigation, Metaphor-aware navigation

1. INTRODUCTION

Navigation has been defined as "the process whereby people determine where they are, where everything else is, and how to get to particular objects and places".[1] Or, as Rudy Darken put it: *navigation* = *wayfinding* + *locomotion*,[1] wayfinding being "knowing where to go" and locomotion "how to get there". However, Jock Mackinlay, when asked to give a definition for navigation just put it as "navigation is getting lost".[1] In fact, navigation in large three-dimensional worlds is by all accounts far from a trivial task. Thomas West calls it the "the increasingly pressing problem of our age – that is, quickly and effectively navigating oceans and oceans of information".[2]

We present here the navigation strategy developed in the context of the CyberNet project. The CyberNet project is a research project that aims to study how 3D information visualization may help in the visualization of large volumes of dynamic information. The navigation in large virtual worlds constitutes thus one of our major axis of research, as it constitutes a fundamental asset for data exploration. It should be noted that we focus on standard user interface tools (i.e., mouse and keyboard) for the navigation. In other words, we only address the problem of desktop navigation in three-dimensional worlds – we do not consider immersive navigation.

In this paper we introduce our concept of metaphor-aware navigation and describe how, in this context, the system takes care of the locomotion navigation part for the user, by providing different automatic methods for the user to move around in the world. Our navigation implementation also addresses the wayfinding part. It provides means for the user to know rapidly what information is available and how to choose that information as target destination. We further show that we give the possibility to the user for navigating semantically and

Further author information: (Send correspondence to C.R.S.)
C.R.S.: E-mail: Cristina.Russo@eurecom.fr, Telephone: +33 (0)4 93 00 26 26, Web site: http://www.eurecom.fr
P.G.: E-mail: Pascal.Gros@eurecom.fr
P.A.: E-mail: Pierre.Abel@eurecom.fr

physically/metaphorically based, due to a tight binding between the semantical and the physical structure. The close binding of semantical and physical structure has been suggested in previous works for hypertext,[3] for effective view navigation,[4] regarding wayfinding,[5] and also cyberspace.[6]

This paper is organized as follows: in the next section, Section 2, we refer prior research done in the area of navigation in electronic worlds. In Section 3 we present the data model used in the CyberNet Project, and in Section 4 the visualization model. Section 5 addresses the metaphor-aware navigation concept, as well as how we combine semantical and physical/metaphoric navigation in CyberNet. Finally, in Section 6, some conclusions are drawn.

2. PRIOR WORK

Prior work done in the field of three-dimensional navigation focused mainly in viewpoint manipulation. Spatial knowledge is another subject that has also been addressed in several research work dealing with electronic navigation. Related research works have focused primarily in the issue of constrained navigation. This section presents previous work regarding these three subjects, as they are closely related to the navigation research done in the context of CyberNet (e.g., "look at" navigation mode, survey knowledge, helped navigation). We also refer previous work addressing semantical and physical structures and navigation.

Hand[7] reports most of the work already done on viewpoint manipulation. Navigation tools can be classified as being egocentric (moving a viewpoint through the world) or exocentric (moving the world in front of a viewpoint). They are also classified in terms of general movement (exploratory), targeted movement, specified coordinate movement and specified trajectory movement.

Most of the navigation tools implemented by VRML (Virtual Reality Modeling Language) browsers fall in the egocentric category[8] and the movements allowed have names such as fly, pan, walk or examine. General movements require to fix all the viewpoint parameters but one, and to let the user modify the value of that specific parameter using the mouse or the keyboard. Some targeted movements (such as 'fly to' with direct selection of the target, or 'jump to' with a list of viewpoints for target selection) are already supported. Although they may exploit the 3D world to simulate gravity or collision, these navigation mechanisms are completely independent of the virtual environment itself.

Spatial knowledge has been classified in three classes[9]: landmark knowledge (being able to identify positions using visual cues), route knowledge (having a knowledge of spatial relationship between visual cues) and survey knowledge (having a global spatial understanding of the environment).

Regarding position awareness, different kinds of solutions have been investigated. The main idea is to provide visual feedback of the user position. The simplest feedback scheme is to permanently display the 3D coordinate position of the user. This solution is not of great help especially because this position only has a meaning if the user already has an in-depth knowledge of the world geography – survey knowledge. More elaborated solutions are based on the display of a global, simplified view of the world added in the user's field of view. Stoakley et al.[10] propose the use of a "World In Miniature". Satalich[11] studied how two-dimensional maps could help users to navigate in virtual buildings. Another research work[12] presents the concept of a "map view", a tool that allows the user to monitor his position (viewed from a "satellite" position) on a small virtual screen embedded in the 3D world.

Although there are differences among these methods, the underlying idea is to include – in front of the user – a small overall view of the world and a marker showing the position of the user in that world. For orientation awareness, Murta[13] has pointed out the importance of the knowledge of the vertical direction and presented some "upward" cues such as ground planes, backdrops and directional illumination.

The concept of "trailblazing" has also been proposed.[12] The basic idea is to allow the user to leave graphical markers (that act as user defined landmarks) in the 3D world. The use of landmarks can be compared to the use of hyperlinks in HTML (HyperText Markup Language) documents, trailblazers being some kind of equivalent to the user's bookmarks proposed by HTML browsers.

Allowing a user to navigate freely in the environment is important, but most of us have experienced that being "as free as a bird" is not that easy. Research has been done in order to enhance the navigation activity

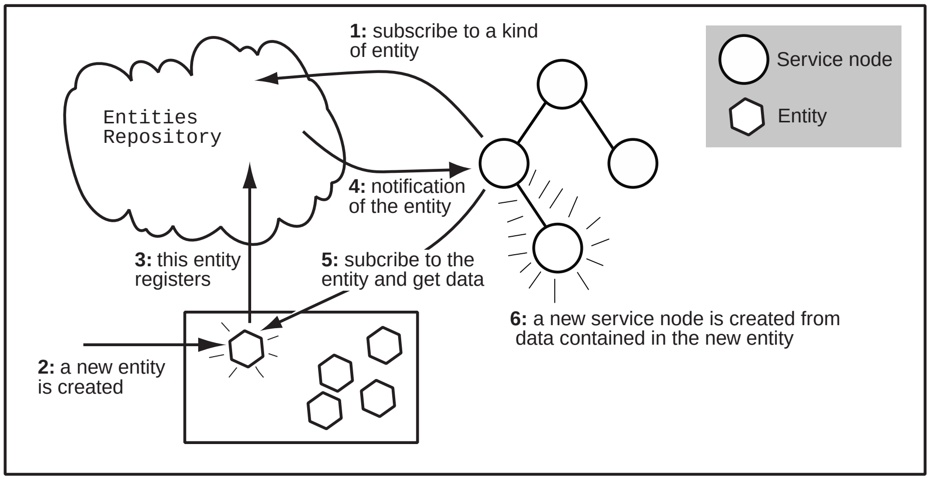

Figure 1: Construction of a service tree.

by taking into account the goals of the user. The solution is generally referenced by the term *constrained navigation*. Although it is true that these methods generally put constraints on the user movements, we prefer to use the term *helped navigation*, as the final goal is not to constrain the user movements, but to help him navigate more easily and efficiently.

Some early work towards the direction of helped navigation is reported in prior research.[7] Kaye[14] presents the "tracking viewpoint"; the idea is to modify the user's direction of view in order to allow the user to track a specific object – potentially moving – in the scene. In other words, the system provides an automatic cameraman that follows an object in the scene. This idea was also presented[12] for tracking the user position in order to control the "map view". Hanson et al.[15] presents a tool that constrains camera movements so that the position is limited to a surface and the orientation is dependent upon the surrounding objects. This study has been done mainly in the context of terrain navigation. The authors conclude that this kind of help tools should be context-dependent, state-dependent and history sensitive.

Dillon et al. argue that "ultimately, we believe that the idea of directly navigating semantical space has to be spurious" in research work addressing hypertext navigation. Furthermore, "in effect we cannot navigate semantic space, at least not in the way we navigate physical environments, we can only navigate the physical instantiations that we develop of the semantic space" and they recommend that a well designed hypertext system entails a strong correspondence between its semantical and physical structure. The same recommendation has been made for wayfinding,[5] cyberspace,[6] and effective view navigation.[4]

3. DATA MODEL

The visualization of abstract data involves translating the data into visual elements. This translation requires several steps. The first step towards this process is to logically structure the data in order to obtain a data model – this step has been referred to as *data transformations*.[16]

CyberNet's information structure is based on the concept of services. The concept of a *service* arose thus from the need of structuring the raw data in order to be visualized in a metaphoric representation. A service is hence just a way of structuring information in a manner that is more easily exploitable for its future visual representation.

The service structure is a tree, composed of entities, relations and service nodes:

- *Entities* are the smallest building blocks that are used to construct the service tree. Entities gather related information concerning an element of the service and may have one or more attributes.

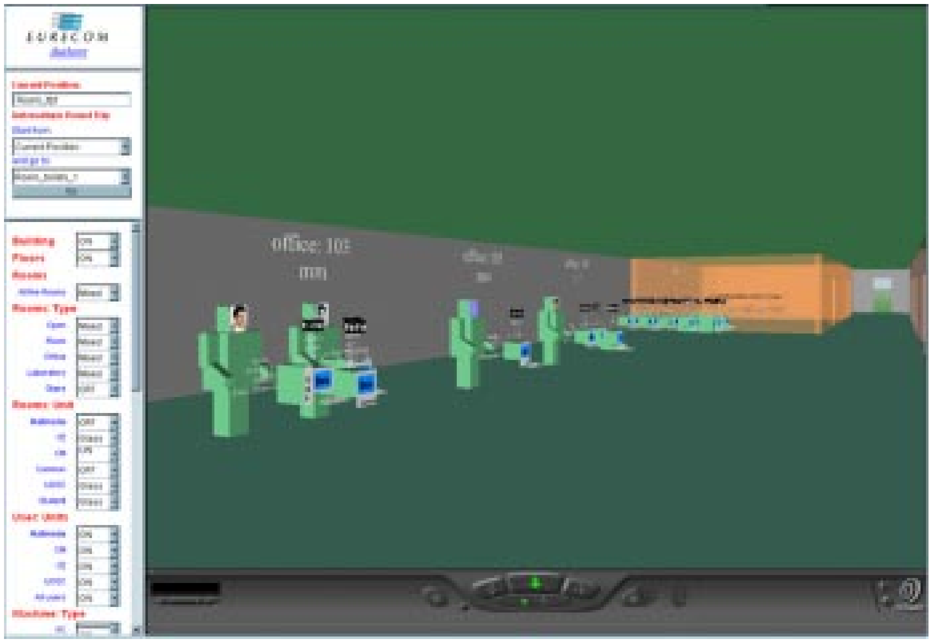

Figure 2. Visualization of network devices, machines, offices, and staff information at Eurécom Institute. Virtual building metaphor – CyberNet project

- *Relations* are the "glue" that is used to build the service model tree. Relations gather entities according to a common characteristic (entity attribute). Thus, a relation is a reference to one or more entities and an entity can be involved in one or more relations.
- *Service nodes* are the nodes of the service tree. Service nodes use the service elements (entities and relations) to build the service tree. Each service node is related to at least one relation and is therefore aware of all the entities involved in the concerned relations.

Entities are then used to group all the values that are necessary to describe some logical element of the data model. An entity can represent a physical device (e.g., a router, a hub) or a conceptual item (e.g., a process, a file-handle). The entities are created by an entity collecting process and are stored in an *entity repository*.[17] The role of the repository is to keep track of all the existing entities and to be able to answer to queries concerning entities (i.e., all the hubs that have an IP address in a given range).

The way the service tree is constructed is the following: the service node issues a persistent query to the entity repository, the repository returns what we call a relation, which groups references to all the entities that satisfy the query. The service node adds that relation as one of its children, hence constructing a tree-like structure. Figure 1 depicts this mechanism.

4. VISUALIZATION MODEL

CyberNet's visual representation is supported on the use of visual metaphors. Our conceptual system is fundamentally metaphorical in nature.[18] The use of visual metaphors makes appeal to underlying concepts the user is already familiar with. This facilitates the comprehension of the visual representation of the information. Moreover, the use of visual metaphors for information visualization helps the user predict the behavior of the information system and acquire its affordances. It is worth noting that most of the information that we deal with in the context of the CyberNet project[19] (e.g., network management data, web server logs) is abstract information – i.e., with no natural physical representation. Hence, there is the need to somehow map the abstract data onto the visual parameters of the virtual world. But the world itself must have a structure that "holds it together" and renders it intelligible – a metaphor.

4.1. Metaphoric Worlds

CyberNet virtual worlds use mostly real-world based metaphors since their underlying structure is familiar to the user. We have designed real-world metaphors such as a building (Figure 2), a city (Figure 6) or a solar system. Nevertheless, it is sometimes more useful to use abstract metaphors, such as a conetree,[20] specially for depicting hierarchical information. Therefore, the CyberNet system also uses more abstract metaphors as the already cited conetree or an information landscape (Figure 3). The choice of the metaphor depends essentially on the information to be displayed and the user's task.

4.2. Metaphoric Components

The navigation mechanisms developed for the CyberNet project are deeply embedded in the metaphor itself. We feel that the way a user moves in an electronic world is intimately related to the visual assumptions, thus to the metaphor, present in that world. In CyberNet, the metaphor structure is described by a tree, which fits the structure of the scene description graphs found in most 3D libraries.

We use two kinds of objects to build a visual metaphor: layout managers (LMs) and 3D Glyphs (3DGs). Layout managers are responsible for the virtual space management and their major task is, thus, placing their children (either other LMs or 3DGs) in space according to their capacity; e.g. a `stack.Y` LM piles up its children along the Y dimension. In the metaphor description tree, layout managers correspond to internal nodes. 3D Glyphs are three-dimensional graphical elements that allow for information mapping, via the visual parameters they possess (e.g. color, shape, size). In the metaphor structure, 3DGs correspond to the leaves of the tree.

Metaphoric components are the graphical elements of a metaphor, i. e., 3D glyphs and layout managers, with embedded interaction and navigation capabilities. Thus, according to our terminology, metaphoric components and graphical elements of a same metaphor do not exactly mean the same thing, from a theoretical point of view.

Graphical elements are just the basic elements that are used to construct a metaphoric virtual world and serve to visually map the information. Metaphoric components are all the graphical components of the metaphor, but we consider that this type of components must have embedded interaction and navigation features, if the case applies. As an example, a rectangular box may be a graphical element (3D glyph) for constructing a given metaphoric world (e.g., a virtual building). But that rectangular box when instantiated in the same metaphor to play the role of a floor with navigation features (e.g., moving the user along the floor's corridor) is then perceived by our system as a metaphoric component. This latent ambiguity of the metaphoric components goes to the encounter of the argument that states that contrary to Graphical User Interfaces (GUIs), electronic worlds contain objects function both as navigational and destinational.[6] This king of multipurpose propriety of electronic worlds elements has also been advocated in other research[21] [4] . It should be noted that metaphoric components also provide additional functionality, not related to the navigation (e.g., built-in interaction mechanisms), thus beyond the scope of this paper. For further information on this (and other) topic please refer to the CyberNet's project webpage.[19]

5. METAPHOR-AWARE NAVIGATION

When the user navigates from office to office in a virtual building he does not use the same navigation mechanisms as when he is exploring a landscape of data or studying the topological structure of a cone tree. Our belief is that navigation mechanisms should be dependent on the metaphor and embedded in the graphical components of the 3D world. The goal is that the user navigates in the world with the mechanism most suited to that particular metaphor. We call this principle *metaphor-aware navigation*.

One of the easiest ways to understand the idea behind metaphor aware navigation is to consider path-based navigation in a building. When a user wants to go from his current position to another office, he generally follows some logical path through the stairs and corridors (see Figure 4). Following this path (as opposed to

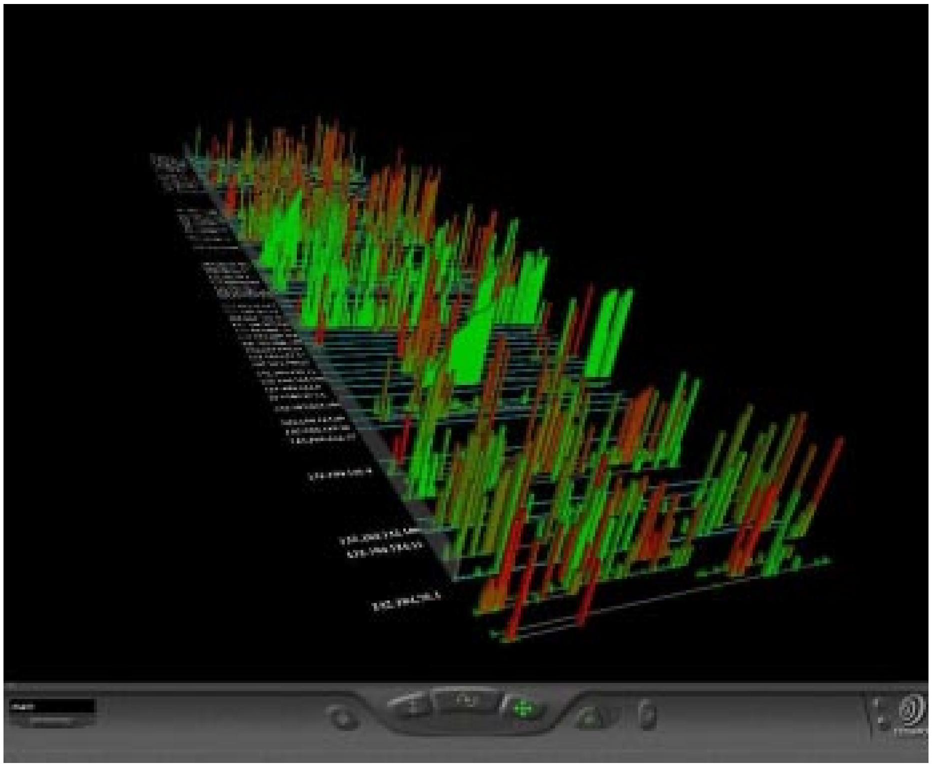

Figure 3: Visualization of network traffic data. Information landscape metaphor – CyberNet project.

instantaneous jumping) is important since it gives to the user the knowledge of the relative location of the objects in the virtual space – route knowledge. Using traditional navigation tools, this kind of navigation is not an easy task. Our metaphor-aware navigation system will help the user accomplish his task: the system will automatically route him along the right path in the building and will take care of the details of the navigation (e.g., turn, go down, and so on). It should be noted that the path taken by the user in our metaphor-aware navigation system is a "feasible" path from the point of view of real world constraints (e.g., there is no wall traversing, no ceiling or floor crossing, and so on).

The basic principles we took into account when designing the CyberNet navigation tools were the following:

- Navigation tools should be adapted to the metaphoric world and may sometimes mimic real world navigation. This helps preventing user disorientation. We gave an example based on the building metaphor in the previous paragraph, where route knowledge is enforced by the path navigation mode, in which the user navigates in a manner similar to the real world. This goes in the same direction as former research that argued that user knowledge of how to behave in certain environments (e.g., roads must be crossed at a pedestrian crossing) must be tied to the navigational schemata.[3]
- Different navigation schemes may be used for navigating at different levels of the metaphoric world hierarchy. This kind of navigation is helpful to acquire different levels of spatial knowledge. For instance, in a town, the user may navigate at the district level, like a bird flying over the town (see Figure 5), or he may navigate at the street level (see Figure 6), walking in the streets in order to go from one building to another. The user will have a global view seen from far away – survey knowledge – when he is navigating at the district level, and a narrowed, more local view – route knowledge – when navigating at the street level. These two different levels of navigation support the distinction made in previous research[22] between the two main types of spatial knowledge: route and survey knowledge.

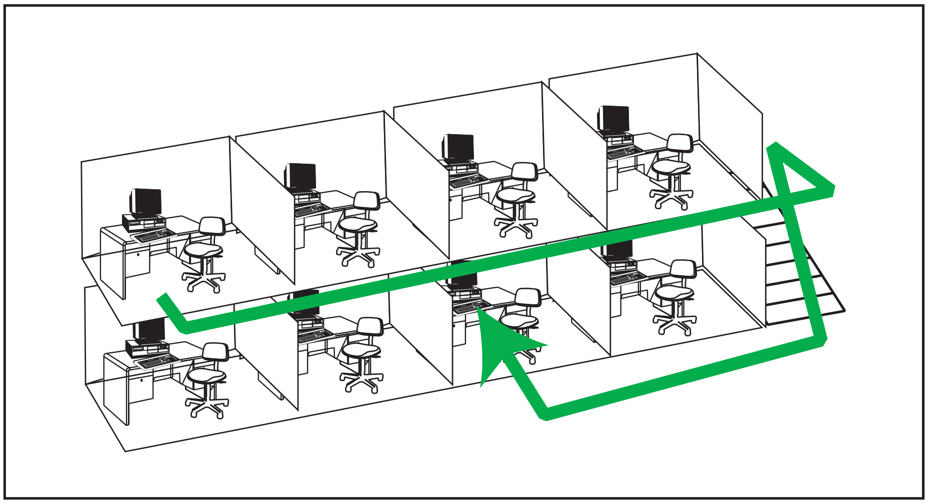

Figure 4: Moving between offices in a virtual building with the metaphor-aware navigation path.

- Navigation tools should take advantage of the metaphor hierarchical world and provide schemes to navigate through the various levels of the hierarchy. The user will then benefit from his knowledge of the underlying structure of the world, which matches the service hierarchy, to navigate semantically in the virtual world. He may just use a navigation interface proposing standard movements in the hierarchy (i.e., up, down, next, and previous).
- Navigation tools should help the user when he has a specific navigation task and should handle the navigation details for him – i.e., they provide the locomotion for the user.
- The navigation tools should take advantage from the fact that, although sometimes based upon the real world, the virtual worlds pose fewer constraints to the user (e.g., gravity, size, and speed). This is the case with the "jump to" navigation mode, which basically takes the user to the target destination instantaneously; this is in opposition to the path mode, that takes the user along a metaphor-dependent feasible path. The navigation tools must also take into account the fact that the user may change the virtual world.

5.1. Helped-Navigation Control

In order to assist the user in his navigation task, the system must know the *user's current state*. We define the user's current state as constituted by three parameters: the *user's current location* in the 3D world, his *current node of interest* (the node that currently has his attention) and a *new node of interest* (the next target of his attention).

When the user is simply moving around in the world, the user's current node of interest and his current location are identical. But some navigation tasks require the user to be located in a place and to have his node of interest on another object; an example is the "look at" navigation mode, which is a case of exocentric navigation by viewpoint manipulation. The basic functionality of the navigation system is to allow the user to modify his current state (current location and node of interest), by choosing a new node of interest.

Our helped navigation mechanism is target oriented: the user should specify a *node of interest*. This node of interest is a node in the metaphor hierarchy that can either be the destination of a movement or an object to look at. In CyberNet, the node of interest can be defined using two basic mechanisms. *Absolute selection* allows the user to identify an object by its name (using a hierarchical VRML-like viewpoint menu) or by direct selection in the 3D space. *Relative selection* allows the user to identify an object by its position in the hierarchy

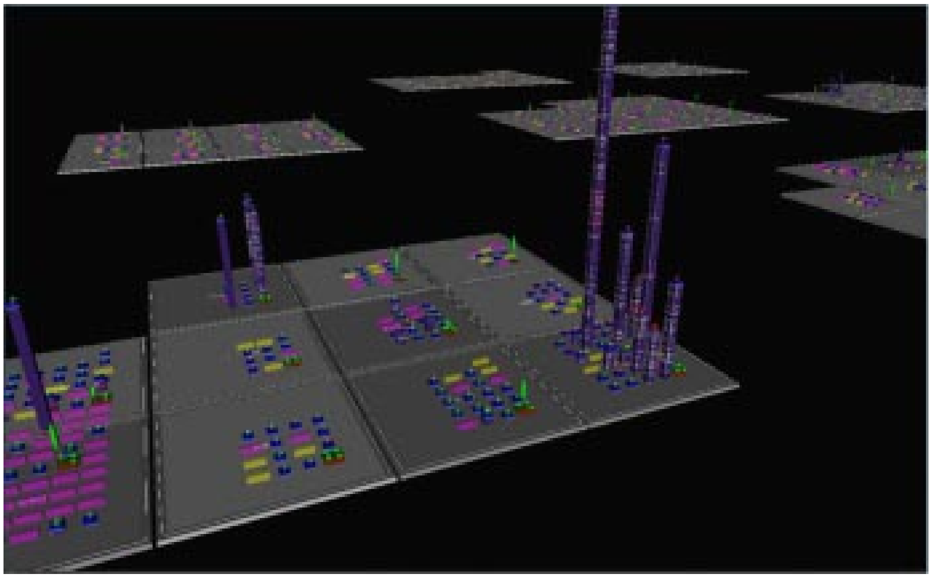

Figure 5: NFS service data visualization. City metaphor – CyberNet Project.

relatively to the previous node of interest. Once a target is defined, the system automatically handles the details of the navigation for the user. For instance, the user is transported to the target location by following a logical path according to the metaphor.

5.2. Target Selection

Absolute navigation requires the user to select a new node of interest using absolute selection: a selection mechanism similar to the one supported by most VRML browsers for viewpoint selection. For this purpose, when a metaphoric component is created it should notify its existence to the system. The system is responsible for offering a scheme to select that new object as the new node of interest. This selection can be done, either by using a 3D embedded interface (by clicking on an object for example), or using an external menu, that is hierarchical and context sensitive. This general mechanism looks like the mechanism supported by VRML browsers for handling viewpoint selection. Once the user has selected a new node of interest, the system has to determine what steps to take according to the current navigation task.

Relative navigation requires the user to select a new node of interest using relative selection: that is the new node of interest is chosen relatively to the underlying world hierarchical structure using traditional browsing operators such as up/down (in the hierarchy), or next/previous (element at that level). For example, when the user is in an office, choosing "next" will automatically take the user to the next office in the corridor, while "up" should take the user to the corridor or to the next floor (according to what the designer has specified as being the higher level). In other words, up/down as navigational aids take the user to the ancestors/descendents of the node in question; in a similar manner, next/previous, will take the user to the adjacent/preceding sibling (element at the same level in the hierarchy).

This relative navigation scheme is important since CyberNet users are aware of the hierarchical service model represented by the metaphoric world. Since the virtual world structure follows the hierarchical service model they may rapidly access points of interest. When using this mechanism the user is actually navigating semantically – he is navigating the service hierarchy, which matches the metaphor hierarchy. The translation of the user action (i.e., "up") into a visual node of interest is metaphor dependent. In fact, what the system does is take the user to the upper hierarchical level (regarding the service structure and mapped onto the visual metaphor structure). This is implemented using a neighboring table provided by each metaphoric component.

The navigation system uses this table to determine the new node of interest and then the absolute navigation algorithm is used.

5.3. Movement Modes

So far, we have only discussed the schemes provided to select the new node of interest. The system will now have to determine a set of movements that should be done within the context of the current metaphor in order to go from the user's current node of interest to that new node of interest. These movements are dependent on combined use of a *user mode* and a *movement mode*. The movements obtained by logically combining these two modes are represented in Table 1.

	Movement mode		
User mode	Jump	Interpolated	Path
Go to	The user jumps to the new node of interest and gets attached to it. (VRML)	The user flies in a straight line from his current location to the new node of interest and his orientation is modified. (VRML)	The user travels from his current location to the new node of interest according to a metaphor-based path.
Look at	The user stays at his current position and looks in the direction of the new node of interest. If the object is moving then it is tracked.	The user stays at his current position. His direction of view is animated from its current value to the direction of the new node of interest.	The user stays at his current location, but his direction of view follows a metaphor-based path from the current node of interest to the new node of interest.

Table 1. Movements obtained by combining the different navigation modes (movements marked VRML are supported by most VRML browsers).

We have seen how our helped navigation system is based on the choice of a target destination – node of interest – with the possibility of specifying intermediate passing points, in the case of the "interpolated" movement mode. If we consider navigation as being the sum of wayfinding (knowing where to go) plus locomotion (getting there), as Darken[1] defined it, then we can say that, in our system, wayfinding is provided by target selection (Section 5.2) and locomotion by the movement modes (Table 1).

We call physical or, more accurately, metaphorical navigation when the user is navigating the virtual world, and his wayfinding decisions (i.e., choosing his target destination) are based on the visual information available, that is, on the metaphoric representation of the data. We refer to semantical navigation, when the navigation decisions made by the user are based on the underlying information structure, as opposed to visible world.

5.4. Physical/Metaphorical Navigation

The user can effectively navigate in the metaphoric world – physical navigation – either by his own means or by taking advantage of the navigation mechanisms that the metaphor provides for him. Namely, the already referred path-based navigation where the metaphoric components take care of moving the user to his target destination according to a logic physical path in the metaphor (e.g., no walls traversing in a city metaphor). The target may be chosen directly in the virtual world by clicking on the desired destination object. This is what we mean by physical navigation, as opposed to semantical navigation – the user is navigating based on the visual

Figure 6: NFS service data visualization. City metaphor – CyberNet Project.

information displayed and not based on the underlying information structure and semantics. For instance, in the case of the NFS service visualization (Figures 5 and 6), the user may directly select a given building as target destination because of its height (height is mapping a data value which accounts for choosing the highest value). This is navigating based on visual information. These are only examples of the metaphor dependent navigation mechanisms that we provide for the user physical navigation. But we also provide mechanisms for navigating based on the actual information structure – semantical navigation.

5.5. Semantical Navigation

The user may navigate thus based essentially on the service information rather than on the visualization of that data. For instance, the user has the possibility to choose to go to every element (service node or entity) of the service tree. The navigation mechanism will take him there in the virtual world according to his choice of navigation mode (e.g., by flying the user to the target). This target option is given in the form of a hierarchical menu that displays the whole service hierarchy, when completely expanded (as it "unfolds" as the user advances/goes down in the service hierarchy). Additionally, the user can also choose to go to the ancestors or to the descendants of a service node or entity (in the case of ancestors, as an entity, being a leaf node, does not possess any descendants). Similarly, the built-in navigation mechanisms embedded in the metaphor will take him there. This allows for a powerful way for exploring and examine relations and dependencies.

6. CONCLUSIONS

We have presented here some of the highlights of the navigation mechanisms implemented in the context of the CyberNet project. Namely, the fact that the user is given a powerful way of exploring the 3D data visualizations by exploiting either the metaphor tree – physical navigation, or the service tree – semantical navigation. The fact that both ways of navigation are combined in a single visualization makes CyberNet's navigation mechanism a very useful resource for data exploration.

The main contribution is that the fact that the navigation system has a strong component of metaphor awareness, and furthermore, is embedded in the metaphoric components themselves, allows for a quasi standard way of navigating metaphoric worlds – thus making our navigation scheme portable to other metaphors.

REFERENCES

1. G. Furnas and S. Jul, "Navigation in electronic worlds," in *Proceedings of ACM CHI 97 Conference on Human Factors in Computing Systems, Workshop 9* **2**, p. 230, 1997.
2. T. G. West, "Knowing what you don't need to know," *Images and Reversals – Computer Graphics Newsletter SIGGRAPH ACM* **32**, Feb. 1998.
3. A. Dillon, C. McKnight, and J. Richardson, "Space—the final chapter or why physical representations are not semantic intentions," 1993.
4. G. W. Furnas, "Effective view navigation," in *Proceedings of ACM CHI 97 Conference on Human Factors in Computing Systems, PAPERS: Information Structures* **1**, pp. 367–374, 1997.
5. R. Passini, *Wayfinding in Architecture*, Van Nostrand Reinhold, 1984.
6. M. Benedikt, *Cyberspace: First Steps*, ch. Cyberspace: Some Proposals, pp. 119–224. MIT Press, 1991.
7. C. Hand, "Survey of 3D interaction techniques," *Computer Graphics Forum* **16**, pp. 269–281, Dec. 1997.
8. J. D. Mackinlay, S. K. Card, and G. G. Robertson, "Rapid controlled movement through a virtual 3D workspace," *Computer Graphics* **24**(4), pp. 171–176, 1990.
9. P. W. Thorndyke and S. E. Goldin, "Spatial learning and reasoning skill," in *Spatial Orientation: Theory, Research, and Application*, H. L. J. Pick and L. P. Acredolo, eds., Plenum Press, New York, 1983.
10. R. Stoakley, M. J. Conway, and R. Pausch, "Virtual reality on a WIM: Interactive worlds in miniature," in *Proceedings of the Conference on Human Factors in Computing Systems (CHI'95)*, I. R. Katz, R. Mack, L. Marks, M. B. Rosson, and J. Nielsen, eds., pp. 265–272, ACM Press, (New York, NY, USA), May 1995.
11. G. Satalich, "Navigation and wayfinding in virtual reality: Finding proper tools and cues to enhance navigation awareness," Master's thesis, University of Washington, 1995.
12. J. D. M. Edwards and C. Hand, "MaPS: Movement and planning support for navigation in an immersive VRML browser," in *VRML 97: Second Symposium on the Virtual Reality Modeling Language*, R. Carey and P. Strauss, eds., ACM SIGGRAPH / ACM SIGCOMM, ACM Press, (New York City, NY), Feb. 1997. ISBN 0-89791-886-x.
13. A. Murta, "Vertical axis awareness in 3d environments," in *Framework for Immersive Virtual Environments '95*, pp. 169–176, (London), 1995.
14. T. Kaye, "The tracking viewpoint: http://reality.sgi.com/tomk/demos/vrml2/trackingviewpoint."
15. A. J. Hanson and E. A. Wernert, "Constrained 3D navigation with 2D controllers," in *IEEE Visualization '97*, Oct. 1997.
16. S. Card, J. Mackinlay, and B. Shneiderman, "Readings in information visualization: Using vision to think," 1999.
17. P. Abel, P. Gros, C. R. D. Santos, D. Loisel, and J.-P. Paris, "Automatic construction of dynamic 3d metaphoric worlds: An application to network management," in *Visual Data Exploration and Analysis VII*, R. Erbacher, P. Chen, J. Roberts, and C. Wittenbink, eds., **3960**, pp. 312–323, SPIE - The International Society for Optical Engineering, Jan. 2000.
18. G. Lakoff and M. Johnson, *Metaphors We Live By*, Chicago : University of Chicago Press, Chicago, 1980.
19. CyberNet, "Project's webpage http://www.eurecom.fr/~abel/cybernet."
20. G. G. Robertson, J. D. Mackinlay, and S. K. Card, "Cone trees: Animated 3D visualizations of hierarchical information," in *Proc. ACM Conf. Human Factors in Computing Systems, CHI*, S. P. Robertson, G. M. Olson, and J. S. Olson, eds., pp. 189–194, ACM Press, 28 Apr.–2 May 1991.
21. *Humanscape – Environments for People*, ch. A City is Not a Tree, pp. 377–402. Ulrich's Books Inc., 1982.
22. P. W. Thorndyke and B. Hayes-Roth, "Differences in spatial knowledge acquired from maps and navigation," *Cognitive Psychology* **14**, pp. 560–589, 1982.