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Presence of Mind...

a reaction to Thomas Sheridan's "Musings on Telepresence"

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Abstract

In an initial section, operators' sense of remote presence during teleoperation or use of virtual environment interfaces is analyzed as to what characteristics it should have to qualify it as an explanatory scientific construct. But the implicit goal of designing virtual environment interfaces to maximize presence is itself questioned in a second section in which examples of human-machine interfaces beneficially designed to avoid a strong sense of egocentric presence are cited. In conclusion, it is argued that the design of a teleoperation or virtual environment system should generally focus on the efficient communication of causal interaction. In this view the sense of presence, that is of actually being at the simulated or remote workplace, is an epiphenomena of secondary importance for design.

1 Introduction

What are the benefits and significance of developing a reliable measure of the human sense of presence in an environment? Such a scale could measure the extent to which users of a telerobotics interfaces feel or behave as if they were present at the site of their remotely controlled robot. Such a measurement might provide a tool for guiding design of human interfaces for teleoperators and virtual environments. By focusing attention on *telepresence* and *virtual presence*[1] such measurements might also provide insights into the nature of presence in the real world. These are some of many plausible reasons to search for a measurement of presence.

The following essay examines in Sections 2- 5 some characteristics a measurement scale of "presence" ought to have to be useful as an explanatory scientific concept. It also addresses in Section 6 the utility of worrying about developing such a scale at all. To be useful in the same manner as a traditional scientific concept such as mass, it is argued that measures of presence not only need to be precisely defined and co-vary reliably with determinative factors, but also need to establish equivalence classes of their independent constituents. This simplifying property is important for either subjective or objective scales of "presence" and can generally obtain only if the constituents of presence are truly independent. But, as discussed below, constituent independence itself is not sufficient to guarantee the utility of the equivalence classes. In Section 6 the general utility of designing virtual environment interfaces to maximize "presence," even as measured by a scale that meets the standards required, is questioned through the citation of two counterexamples in which commuication is improved through decreased presence.

[1]Italicized words and phrases are terminology used by Sheridan and his students. Their definitions are followed within this paper.

2 What is "Presence?"

Thomas Sheridan's "Musings on Telepresence" (1992) addresses the benefits and significance of developing a scientifically useful measure of presence and identifies its value in teleoperation applications. Presence is considered the sense of actually being at a remote or synthetic workplace which users of *telerobot* or *virtual environment* systems developed during operation of the system's human interface. Since users of a virtual environment interface are in the same position with respect to simulated effectors in the virtual environment as that of human telerobotics controllers with respect to a remote robot, the questions addressed by Professor Sheridan also may be generalized to include operators of *virtual environments* as well as *telerobots*. Accordingly, the two control situations will be subsumed under the term *virtual environment* for the purposes of the following paper. This subsumption is reasonable since with respect to the various users' physical viewpoints in neither case is the depicted environment actually surrounding them. It is virtual, albeit often of differing levels of fidelity (Ellis, 1991). With respect to the perceptual virtualization of the display both control situations are identical. Of course, there is the proviso that the users' knowledge that the displayed information comes from a real source certainly must have a significant impact on their subjective impressions and their performance. Pilots, indeed, fly real aircraft differently than they "fly" aircraft simulators (Stark, 1993) and crashing a real aircraft, even by remote control, is unquestionably different from "crashing" a simulation.

The following essay examines how Prof. Sheridan's conceptualization of "presence" may be extended to an explanatory scientific concept. Some may object that this standard may be too high and it is certainly true that there exist useful measurement scales that might fail to meet such a rigorous standard, e. g. the Cooper-Harper scale of aircraft controllability (Cooper & Harper, 1969; McKinnon & Kruk, 1993) or other similar subjective scales such as the NASA TLX workload scale, (Hart & Staveland, 1988). Even the long established intelligence quotient (I.Q.) may be considered a dimensionless index that only may serve as an explanation of human intellect in a tautological, statistical sense. But as will be argued below, utility accompanies explanatory value. And a high standard certainly provides a challenge for research and development.

The discussion below of the characteristics of presence also addresses the utility of worrying about it at all. Since the essential role of the interfaces in question may be argued to be efficient, effective communication between the operator and the remote robot/simulation program, measurement of the sense of presence might be irrelevant indeed. Only if the scale of presence can correlate usefully with performance and provide a means to aggregate into equivalence classes a number of the influences on effective communication and control does such a scale have a compelling role in interface design. This simplifying property is important for either subjective or objective scales of "presence."

As a final proviso, it should be noted that the discussion below will exclude virtual environment interfaces devised for purely artistic or other goals in which the focus of design is on the "impression" communicated by the interface or the social impact of the medium itself. The following essay is, thus, limited to the case in which the users of a media really are trying to communicate a precise, often numerical message, and are more concerned about error than appeal or impact.

Discussions of virtual environment interfaces generally benefit from clear terms and avoidance of oxymoronic, buzzwords such as "virtual reality." Accordingly, to understand whether measurement of a sense of presence engendered by a virtual environment interface can become a useful concept, it is helpful to discuss briefly the meaning of the terms *virtual* and *environment*.

3 A Meaning for *Virtual*

A clear meaning for *virtual* as used in this essay may be based on a more general concept: *virtualization* which can be considered the *process by which a viewer interprets patterned sensory impressions to represent objects in an environment other than that from which the impressions physically originate.* This definition is abstracted from that of a virtual image as classically defined in geometrical optics. A viewer of such an image sees the rays emanating from the virtual image as if they originated from a point displaced from their actual physical origin.

Virtualization most clearly applies to the two sense modalities associated with remote stimuli, vision and audition. In audition, as in vision, stimuli can be synthesized so as to appear to be originating from sources other than their physical origin (Wightman & Kistler, 1989; Wenzel, 1991). But carefully designed haptic stimuli that provide illusory senses of contact, shape and position clearly also show that virtualization can be applied to other sensory dimensions (Lackner, 1988). In fact, one could consider the normal functioning of the human sensory systems as the special case in which the detection of physical energy and the interpretation of patterned sensory impressions results in the perception of real objects in the surrounding physical environment. In this respect perception of the physical environment resolves to the case in which through a process of systematic doubt, it is impossible for an observer to refute the hypothesis that the apparent source of sensory stimulus is indeed its physical source.

As objects be virtualized, so too may the abstraction within which they exist. Their environment, thus, also can be virtualized along a more or less continuous dimension that can serve as a basis for design.

4 Levels of Virtualization

Three levels of this abstract design dimension termed virtualization may be distinguished: virtual space, virtual image, and virtual environments. These levels represent identifiable points on a continuum of virtualization as synthesized sensory stimuli more and more closely acquire all the characteristics of objects in a real environment. As more and more sources of sensory information and environmental control are available, the process of virtualization, reviewed in more detail elsewhere, can be more and more complete until the resulting impression is indistinguishable from physical reality (Ellis, 1991; 1993). (See Figure 1). Recent considerations of the difficulty of distinguishing high fidelity synthetic environments from physical reality have suggested that the distinctiveness of a displayed environment from reality might itself lead to a technique to measure presence (Schloerb, 1995). In general, the more complete virtualization in a virtual environment compared to that of a virtual space could be expected to correlate with an increased sense of presence.

In the most complete form, the virtualization of an environment, the key added sources of information are observer-slaved motion parallax, depth-of-focus variation, and wide field-of-view without restriction of the field of view. If properly implemented, these additional features can be consistently synthesized to activate the major space-related psychological responses and physiological reflexes such as accommodative vergence, the "near response", the optokinetic reflex, the vestibular-ocular reflex, and postural reflexes. When coordinated, synthesized sound sources are added to these features the result can be a powerful illusion of *telepresence* (Bejczy, 1980).

Successful synthesis of an environment to trigger these spatially related responses, and possibly to induce a sense of presence, can be organized by attention to the parts that make up the environment itself: its *content*, its *geometry*, and its *dynamics* (Figure 2.). These three components have been examined elsewhere (Ellis, 1993; 1994) but in a computer simulation of a physical environment respectively correspond to 1) the graphic objects that are the elements of a simulation, 2) the kinematic description of and constraints on these objects, and 3) their rules of interaction during the exchange of energy or information.

Measurements of the degree to which the content, geometry and dynamics of a virtual environment display convinces its users that they are present in a synthetic world can be made in a variety of ways. One possible technique suggested by the previously proposed defining conditions of a virtual environment is to measure the degree to which automatic environmental responses such as visual capture of perceived eye level (Nemire, & Ellis, 1991; Nemire, Jacoby & Ellis, 1994; Slater, Usoh & Steed, 1994), or more socially conditioned reactions such as hand shaking (Sheridan, 1992) can be triggered in it. Such measurements within the virtual environment may be compared to those in corresponding real environment to determine how effectively the virtual environment communicates the conditions of the real environment. This approach can also provide an alternative to the use of subjective scales of "presence" to evaluate the simulation fidelity of a virtual environment display.

Subjective evaluation scales such as the Cooper-Harper rating have been used to determine simulation fidelity of aircraft and related subjective scales have also been used for workload measurement. Recent work has applied these techniques to virtual environments (Rosenberg & Adelstein, 1993; Slater & Usoh, 1994). But these techniques must be used judicially since different scaling techniques can provide inconsistent results which do not generalize well across different raters and different rating situations. These subjective scales often are used differently by different subjects and thus may need calibration of the individual raters to control for biases (e.g. Hart & Staveland, 1988). Slater and Usoh (1994) have already observed such individual variation in presence estimates in virtual environments. Though they have utility for design, such subjective rating scales may be difficult to develop into simple explanatory concepts and stable equivalence classes because of individual variability across the human raters. Precise methods of calibrating the subjective raters, however, might remove this difficulty (Mendel & Sheridan, 1989). In any case both objective and subjective approaches to the measurement of simulation fidelity or presence should be challenged to demonstrate their explanatory value.

5 Summary of Sheridan's Musings

Proponents of the use of virtual environments as human-computer interfaces have suggested that the intensity of their illusion of presence will correspond to the success and utility of the interface. Investigators have suggested, accordingly, ways to identify the components of the sense of presence afforded to the users of virtual environments, for an early example see Zeltzer (1992). But as Professor Sheridan has pointed out, selection of these components is not yet aided by a theory of presence which would describe how these components combine. Indeed, it is not clear whether a sense of presence is just a concomitant of good human-machine communication, whether it is a benign association or simply a distraction. Clearly, measured presence like any useful measure should be objectively repeatable, reliable, robust to irrelevant disturbances and sensibly correlated with measurable properties of simulated environments. And considerable efforts should be invested to ensure that candidate measures also have the best possible scalar properties, ideally a ratio scale.

Nevertheless, the contention of this essay is that catalogs like the above property list for presence are incomplete. Not only should measures of presence covary with their determinants, but also they should be able to remain constant when their determinants covary in compensating ways. This is an essential property of a useful theoretical construct since such constructs can be used not only to predict change in the presence of change but also to predict constancy in the presence of change. This property amounts to the isolation of equivalence classes in the space of the measure's determinants exactly as mass does through the center of mass rule. This property arises from the independence of the construct's constituents.

This property of establishing equivalence classes can be illustrated concretely using the three proposed determinants of presence as identified by Professor Sheridan. He has suggested that three orthogonal factors control the sense of presence in a virtual environment simulation. These may be summarized as 1) the extent and fidelity of the sensory information that may be displayed to the users, 2) the extent and fidelity of the users' control over the sensory information and 3) the extent and fidelity of the users control of effectors in the environment. Figure 3 gives an example of how Sheridan's three components could combine to produce discrete isopresence equivalence classes.

Sheridan's analysis of factors

Presence, or equivalently simulation realism, is particularly useful as it identifies reasonably independent, easily measurable characteristics of communications channels (e.g. Ellis, 1994). The extent and fidelity of sensory information may be instantiated, for example, as the latency, dynamic range, bandwidth of a signal presented in a particular sense modality, say audition. These signal characteristics are especially useful since they can be considered independently of the users' ability to modify them through control of sensor positions. Similarly, one can easily envision operators as having variable abilities to manipulate and modify their virtual or physical environments independently of the sensory fidelity or sensory control. This independence of components will be argued to be an essential characteristic of the components and contrasts with other earlier analyses, for example, the break out of the three components of simulations: autonomy, interactivity, and presence. Autonomy was considered to be a measurement of the ability of actors inhabiting a virtual environment to behave in adaptive ways. Interactivity was considered to be the degree to which the observer could interact with and control parameters of the simulation, such as the position of objects. Presence was considered a rough, collective index of the number and fidelity of sensory input and motor output channels (Barfield, Zeltzer, Sheridan & Slater, 1995). But it is easy to see that this analysis does not isolate independent influences on the fidelity of a simulation. A change in interactivity such as a change in the sampling interval for a sensor is also a change in the sensor's dynamic fidelity and hence is necessarily a change in the presence dimension.

Now it is certainly true that these three influences identified by Sheridan also could be conceivably coupled since, for example, reorientation of an audio sensor, e.g. an ear, relative to a sound field can certainly change its response characteristics which are direction dependent. But such interaction is not intrinsic to the analysis of the separate components since the dependencies could be incorporated into the description of the sensor. Therefore, independence would not necessarily be violated.

The three components identified by Prof. Sheridan are more importantly appealing since they suggest measurement by well-established continuous variables associated with physical sensors and effectors, e.g. bandwidth, latency, dynamic range etc. One may additionally easily imagine that improvements in any of them would lead to improved operator performance, improved realism, and an increased sense of presence within the virtual environment. In fact, with respect to manual control the dynamic requirements of the communication channel are classically known to determine the fidelity of control. Indeed, Prof. Sheridan's analysis immediately suggests large classes of investigations to measure the consequences of performance parameters in virtual environments that could be used to define equivalence classes.

If the components of presence consist of continuous independent variables $x_1, x_2, x_3, ... x_n$, presence, may be visualized as a function $y = P(x_1, x_2, x_3, ... x_n)$. Such a function will define a smooth surface or hypersurface within which level curves of constant values for y will exist. These level curves constitute the equivalence classes and allow aggregation of bundles of the independent variables. Figure 4 illustrates how combinations of two continuous determinants of presence could combine to produce various levels of presence.

In terms of Sheridan's analysis of presence, for example, the fidelity of sensory display could be instantiated as the bandwidth, x_1, or update rate of a visual display. Similarly, the bandwidth or update rate of the control of a virtual effector could provide another potentially continuous variable, x_2 , influencing a measure of presence. For an illustrative simple case let $y = P(x_1,x_2) = a_1\mathbf{x}_1 + a_2\mathbf{x}_2$ where the a_i's are weighting factors. P will then be a plane. Any line in the plane P parallel to the plane defined by $\mathbf{x}_1, \mathbf{x}_2$ will be a level curve for a fixed $y = k = a_1\mathbf{x}_1 + a_2\mathbf{x}_2$. (See Figure 4 for illustration a more complex example). Measurement uncertainty, of course, complicates the determination of level curves in empirical data and adequate replication is required to reduce it.

The practical and theoretical utility of this aggregation can then be tested by finding a behavioral phenomena which is thought to be a function of presence, i.e. of y, which can then be measured for variations of the determinative variables $x_1, x_2, x_3, \ldots x_n$ taking on values within isopresence equivalence classes. Similar measures can be taken for values which cross isopresence boundaries. If the behavior of interest is truly under the influence of presence, it will only show statistically significant variation for those changes that cross isopresence contours.

There are thus two proposed requirements for the identification of the equivalence classes. 1) Measures of presence as a function of its constituents should result in identifiable surfaces or hypersurfaces so as to allow identification of level set equivalence classes and 2) An independent measure of human performance or some other independent characteristics of the virtual environment should be shown to be determined by the equivalence classes. This second requirement is important to establish the validity of the equivalence classes traced out by the level sets. Without a demonstration of a link to external behaviors, the equivalence classes are merely mathematical entities and theories using them have no physical or behavioral basis.

In fact, there are examples of such equivalence classes in the psychophysical literature. Probably the most appropriate, since it concerns integrated visual-motor behavior of the sort that could take place in a virtual environment, is the index of difficulty, 2A / W, in Fitts Law (Fitts, 1954). In this index A is the amplitude of a repetitive hand movement and W is the required precision. Fitts showed in his original paper that the movement time, MT, for the repetitive movement was a linear function of the index of difficulty for a range of distances and precision[2], notably pointing out that the movement time did not depend on the specific values of A or W and that changes in either independent influence on the transit time could be traded off against the other. In Fitts case MT is the behavioral phenomena. The index of difficulty names the equivalence class. Distance and width are the constituent factors.

6 Presence and Design

A large part of the interest in establishing a scale to measure operators' senses of presence in virtual environments rests on the presumption that conditions with enhanced presence will contribute to effective display and control of objects presented via virtual environments. But since the focus of a virtual environment interface is often the effective communication between the operators and the simulated environment, a sense of presence itself may not be the design goal. The following two examples will provide instances in which design choices explicitly made to remove or control specific aspects of the realism of depicted spatial information effectively improve the interface performance. The improvements in performance might be argued to arise from a decrease in "presence."

The first example illustrates geometric and symbolic enhancements designed to improve performance. The second illustrates a dynamic enhancement with the same goal. Neither of these examples is intended to demonstrate that an improved sense of presence should always be avoided in a display, but rather to argue rather that the unique communications requirements of the particular display and control situation may usefully take precedence in the design of an interface for the display and control of spatial information.

6.1 Perspective Air traffic display: Geometric enhancements

The subjective spatial impressions provided by a visualization are particularly important if the display is to be a basis for immediate three dimensional interaction with the actual environment that it depicts. This type of interaction is required of a pilot using a map display to locate nearby air traffic out his window (Ellis, McGreevy & Hitchcock, 1986) and is particularly interesting if the map display is produced with a planar perspective projection.

The specific choice of perspective parameters for such a projection can have a major impact on the subjective ap-

[2]Fitts Law as expressed by Fitts was MT = a $\log_2$ (2A / W) + b and was thought by him to reflect a signal to noise ratio with the distance corresponding to amplitude, A, and the precision, W. to noise. He considered $\log_2$(2A / W) analogous with $\log_2$ (S / N) in formulas for the information capacity in bits of a noisey channel. Later analyses have either derived the law from a recursive targeting error in a sample data control system (Crossman & Goodeve, 1983) or derived it from human operators capacity to realize that a specific target width is a greater proportion of a small step movement than it is of a large step movement. Thus, in this later case, operators can continuously shorten the time allocated for incremental steps as they approach their target (Cannon, 1992).

pearance and objective interpretation of the depicted space. Initial guesses that selection of an egocentric eye point for the projection so as to make the image mimic what the pilot would see out the window however are arguably inferior for overall spatial situation awareness and navigation. Exocentric eye points, for example, are superior for such tasks since the surrounding environment may be scanned at a glance without head movements. Interpretation of such an exocentric display is, however, conceptually more challenging and requires careful study of the perspective display parameters with respect to the specific spatial exocentric judgment task required of users (Barfield & Kim, 1991; Grunwald & Ellis, 1986; McGreevy & Ellis, 1986; Tharp & Ellis, 1990; Prevett & Wickens, 1994)

The optimal parameter settings depend upon the specific spatial judgment task and have been investigated for interactive tasks in which the subject controlled a 3D cursor (Kim et al, 1987; Ellis et al, 1992) as well as more entirely perceptual task in which subjects made the exocentric direction judgments referenced above. Accurate spatial interpretation of the perspective image depends not only upon selection of a viewing direction relative to a projected object which shows an interpretable aspect but also upon appropriate selection of a field of view angle (McGreevy & Ellis, 1986; Ellis, et al, 1993) and upon specific training (Tharp & Ellis, 1990).

In fact, adjusting the field of view angle so that the image correctly reproduces the objects' lines of sight for a viewer does not generally guarantee that the most accurate spatial perception will be achieved. Viewers commonly demonstrate systematic, open-loop errors in exocentric judgments under such viewing conditions. These may be loosely described as "telephoto biases (McGreevy & Ellis, 1986; Grunwald & Ellis, 1986) (Figure 6). Though the origin of this bias may arise from errors the viewers made in estimating the direction from which display projection was made, the errors may be approximately compensated for by introducing a wide-angle distortion into the viewing transformation. This type of compensation is also effected by the required judgment task and has been shown to require an opposite telephoto distortion if the targeting judgment is done egocentrically. This difference appears to arise from a systematic misjudgment of either gaze or body referenced head-azimuth which combines with a 3D map interpretation error (Ellis, Smith & Hacisalizade, 1989; Adelstein & Ellis, 1993).

Another related kind of compensation can be introduced to correct for the errors in egocentric orientation judgments of aspect. Aircraft aspect, for example, is known to be misperceived in perspective displays with the aircraft appearing rotated into the picture plane (Ellis, 1993b). In this case, though, the compensation can be effected through a kind of misplacement of the object, rotating it in a direction opposite to the expected illusory rotation. This kind of display compensation is in a sense a means to present truth through corrective distortions in objects placement. It illustrates a geometric enhancement of the placement transformation in computer graphics in contrast to the viewing transformation enhancements discussed above. The variety of geometric enhancements that may be introduced into pictorial displays are described in Figure 7 with respect to the transformations used by computer graphics systems to produce a perspective image (Ellis, 1989; Robinett & Holloway, 1995).

6.2 Orbital maneuvering planning tool: Dynamic enhancements

In contrast to the air traffic display there are, however, cases in which simply visualizing spatial data is inadequate for interpretation or interaction with it. One example can be found in a display used to visualize small changes in orbital trajectories as required for maneuvering in the vicinity of a space station (Grunwald & Ellis, 1993). The display allows on-site planning of minimum-fuel, multi-burn maneuvers in a simulated multi-spacecraft environment and provides examples of several features usefully incorporated into actual orbital display systems. Significantly, initial versions of the display system which simply presented geometrically and symbolically enhanced perspective images of ego or exocentrically viewed orbital trajectories proved inadequate. The dynamic difficulties encountered in using these early versions to plan orbital changes originated from several causes. The principal one was the counter-intuitive character of orbital motions as experienced in an egocentric relative motion reference frame. Such a relative motion frame of reference is appropriate for the display since the orbital motions are expressed and tend to be perceived in a coordinate frame with an origin at a large proximate vehicle such as a space-station.

From experience in inertially fixed environments, a us
would intuitively assume that even in the relative fram
of reference a thrust in the "forward" direction toward
vehicle ahead but in the same orbit, i.e. in the direction
the orbital velocity vector, would result in a forward m
tion. However, after several minutes, orbital mechani
forces dominate the motion pattern and the purely forwa
thrust moves the maneuvering spacecraft "upwards", i.
to a higher energy orbit. This will ultimately result in
decelerating, backwards relative motion, since by Keple
Third Law objects in a higher orbit move slower such th
for an orbital period, n_o, and average orbital radius, R
$(n_o)^2/(R_o)^3 = k$, where k is a constant. Thus, a forwa
thrust ultimately has the opposite effect from that i

tended. The deviation may be expressed, as is common for astronauts who have personally experienced it during "space walks," as the effect of an "orbital wind."

The difficulties this "wind" and related characteristics pose for missions conforming to operational constraints may be overcome by visualizing the orbital trajectories and constraints in a pictorial, perspective display. But these displays need to be carefully designed to conceal the troublesome aspects of the physical situation. Though a straight forward visualization of these trajectories and constraints can assist planning by providing visual feedback concerning the trajectories and constraints, the most significant, novel features of the display considered here include 1) an *inverse dynamics* algorithm that reduces the order of control while also removing control nonlinearities expected from the operator (Wickens, 1986) and 2) a trajectory planning mode that creates, through a *geometric spread-sheet*, the *illusion of an inertially stable environment*. This schematic environment provides the user with independent control of relevant geometric parameters of way-points during small orbital changes in a manner far superior to a display providing its user with a sense of actual presence in orbit. The "inverse method" is required to compute the values of a burn necessary to arrive at a given way-point continuously positioned by the operator with the aid or a mouse or trackball.

Additionally, multi-vehicle orbital missions are subject to safety constraints, such as clearance from existing structures, allowable approach velocities, angles of departure and arrival and maneuvering burn restrictions due to plume impingement or payload characteristics. Design of a fuel-efficient trajectory which satisfies these constraints is a non-trivial, almost impossible manual task because selection of maneuvering burns to satisfy one constraint can interact the satisfaction of another constraint. However, the introduction of the dynamic enhancement of "sticky" way-points that are automatically updated to preserve their relative position as other changes in a sequence of maneuvers are made has been shown to make manual planning of the task relatively simple and is the essential characteristic making the planning tool a "geometric spreadsheet" (Grunwald & Ellis, 1993b).

7 Summary and Conclusions

As illustrated by the previous two examples, communication effectiveness can be enhanced by displays that control, or even reduce, operators' senses presence at the control site. If flight controllers who are planning an orbital maneuver were asked if they felt present at the remote site, their answer would probably vary widely depending greatly on the question was interpreted, much as do subjective estimates of workload. In the case discussed improved control is achieved by explicitly removing the co trol from the frame of reference of the remote environmer The display works by abstracting the key variables ar parameters that the user must control in a geometrical and dynamically tractable, but schematic, format. It important to emphasize that the difficulties which ma lead designers to develop displays which actually redu the users' sense of presence to improve their interactic within a target environment are not merely that the targ environment is dangerous or difficult. Rather the designe through analysis of the desired causal control which is be communicated reciprocally between the operator ar the environment, has determined that optimal sensor motor transformations should place the user outside c rather than immersed within, the design environment.

Ultimately successful designs of similar enhancements ca be brought into virtual environments. This importation more difficult since users of such interfaces actually liv "in" virtual environments and thus introduce many phys ological and psychological constraints related to postur balance, self-motion perception, and spatial orientatio Clearly, virtual environments are a much more challen ing area for development of symbolic, geometric, or dy namic enhancements than virtual spaces. Consequently measures of presence are to guide design of environment interfaces, the more complete the standards against whic the measure is judged, the better. In virtual environme media where the medium itself is not the message the ke questions to ask may not be whether the users "fee present in the remote or synthetic environment b whether they can accomplish the tasks they accept. Ca they acquire the necessary information? Do they have th necessary control authority? Can they correctly sequen their subtasks? Successful implementation of virtual env ronment simulations will directly depend on the answers these kinds of questions. The degree to which measures presence help guide designers to the correct answers these questions will depend upon the quality of these me sures themselves.

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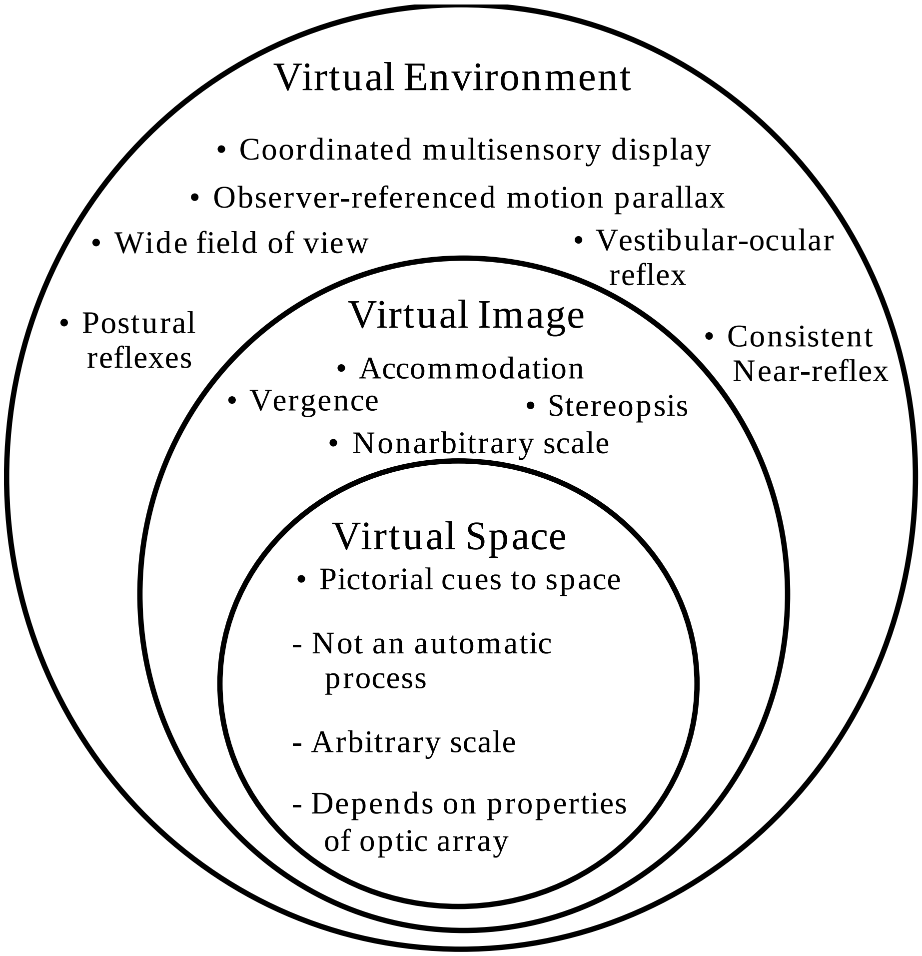


Figure 1. An illustration of how the addition of more and more characteristics of physical reality builds increasingly complete levels of virtualization.

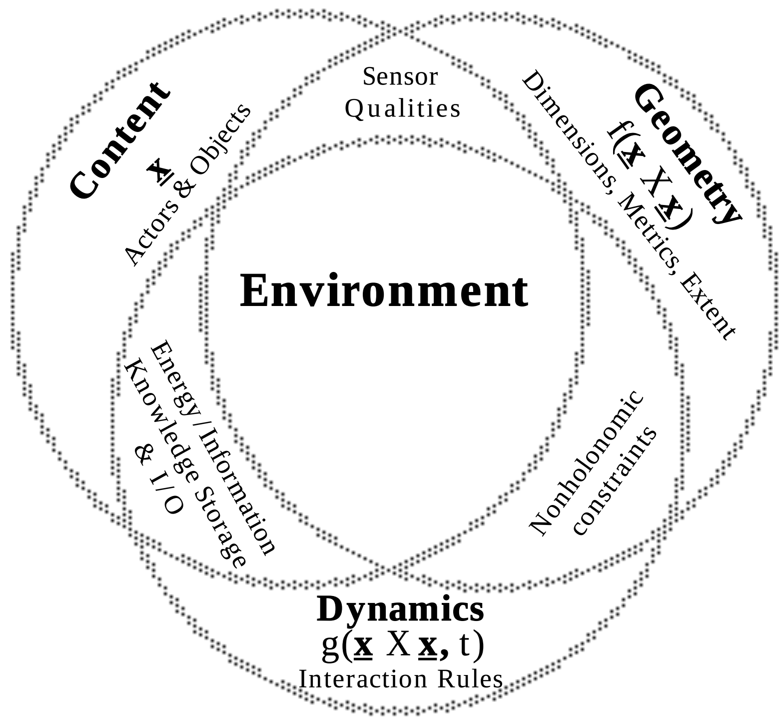


Figure 2. The abstract components of an environment are its content, geometry, and dynamics. The actors and objects making up the content are described by sets of vectors **x** which reflect the values of a series of tests made on each element to describe their position and condition. The geometry of the environment may be described by functions defined on the Cartesian product of the position vectors, **x** X **x** of the elements. The dynamics are defined by similar functions which include time and describe the rules of interactions among the environment's elements.

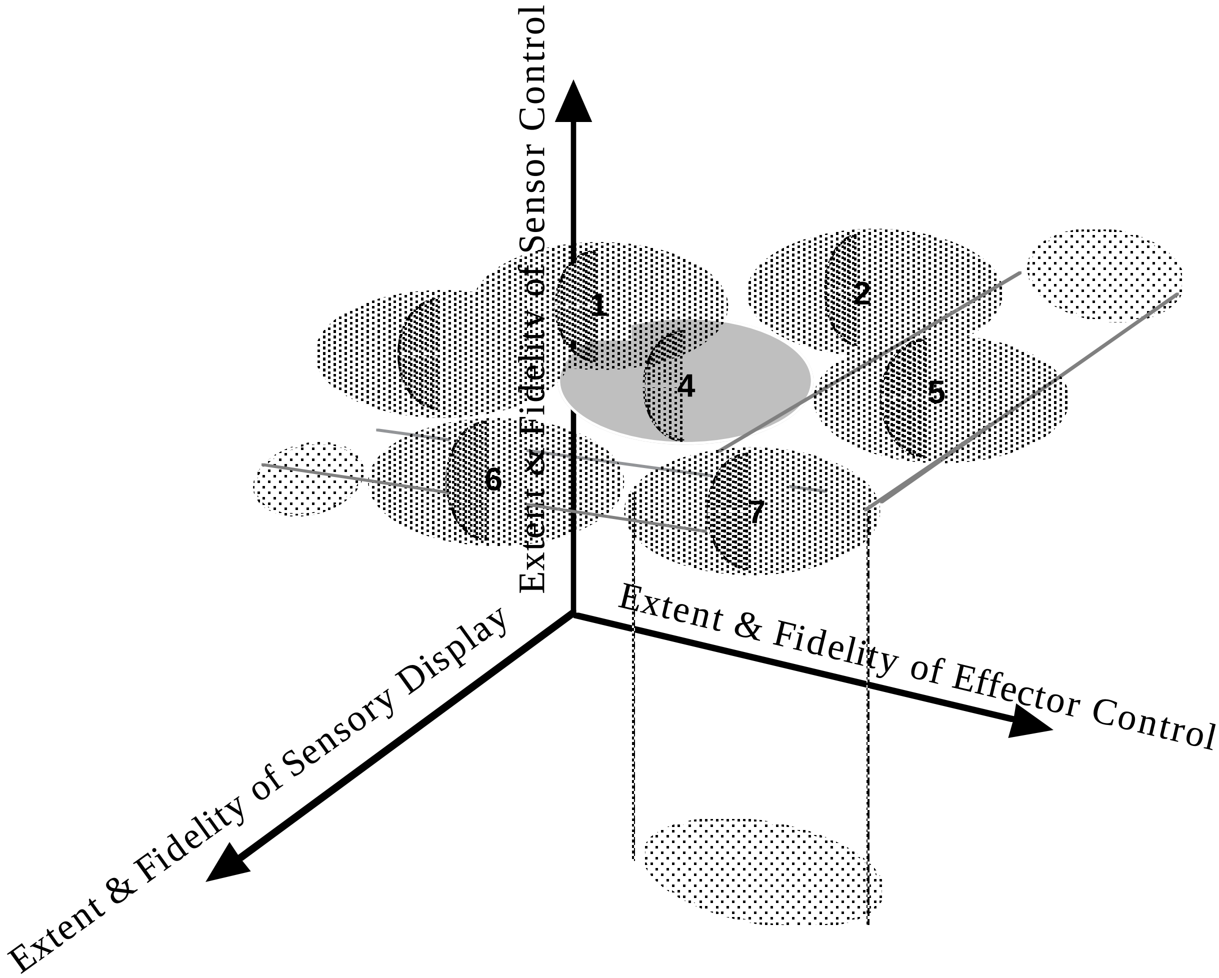
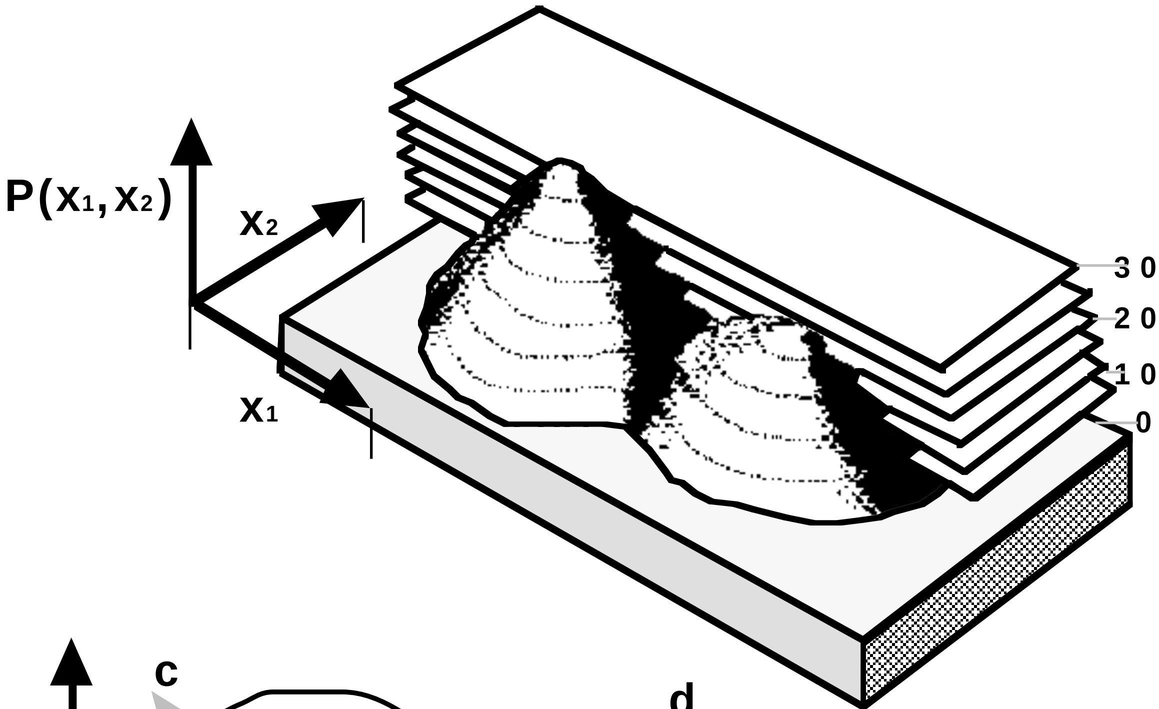


Figure 3. Hypothetical examples of discrete equivalence classes of presence in a space defined by Sheridan's three determinants of presence. Each cloud of isopresence conditions is numbered to give its conjectured level of presence. The projections from presence level 7 illustrate the ranges within which each variable may change so as to keep presence constant at level 7.



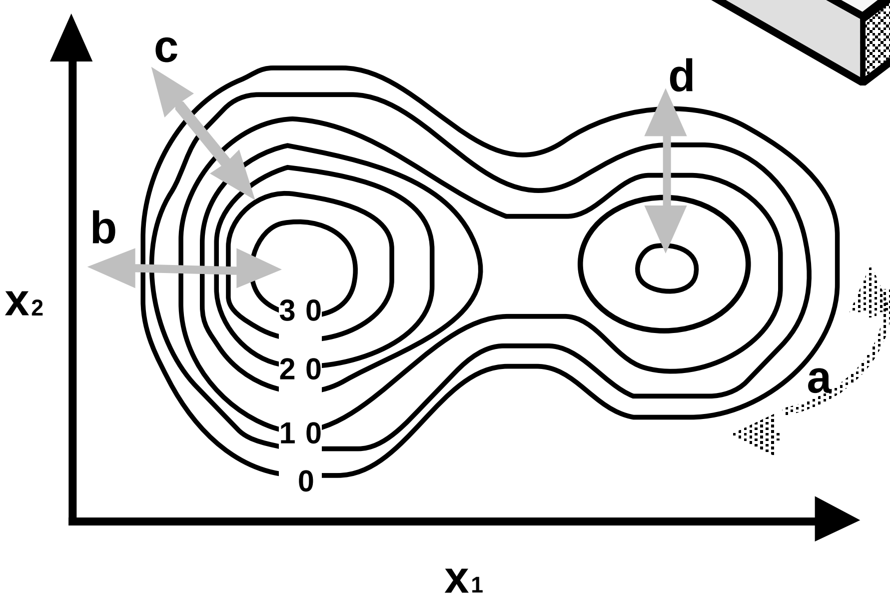


Figure 4. Examples of how isopresence contours (lower image) corresponding to fixed levels may occur on a complex surface (upper image) determined by two independent variables, , contributing to a sense of presence. Positions a and c show ranges where both variable cause presence to change whereas b and d show ranges where only one variable has a major effect.

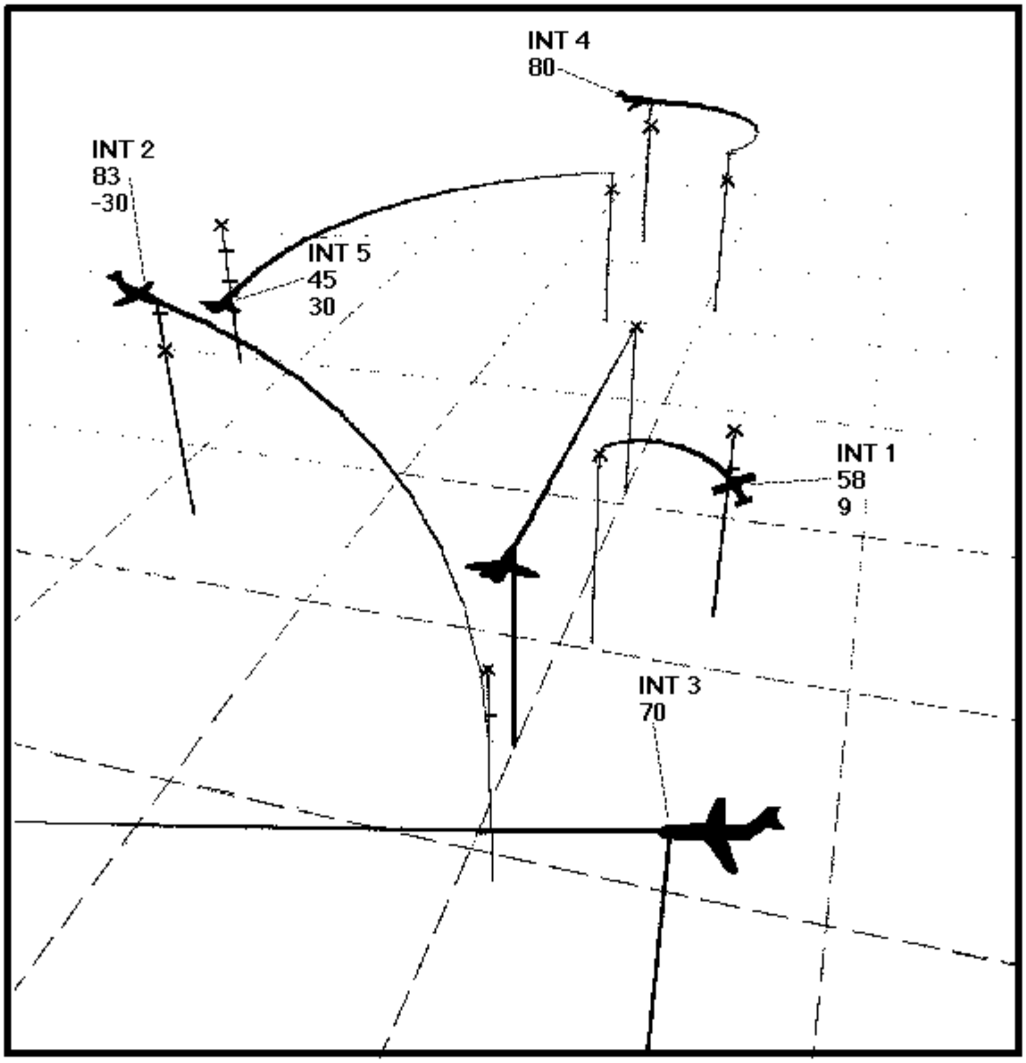


Figure 5. An early example of a cockpit aircraft traffic display presenting an exocentric view of the pilot's own ship, the aircraft in the center of the display, with a variety of "own ship relative" symbolic enhancements. For example, the own ship's altitude is shown as an "x" on all reference lines showing the other aircraft's' height above the reference grid. Each aircraft is provided with a predictor showing its future position in 1 minute. The geometry of the display was designed so that no matter how the field of view angle was changed, a fixed volume of airspace surrounding the own ship was always displayed (McGreevy, 1983).

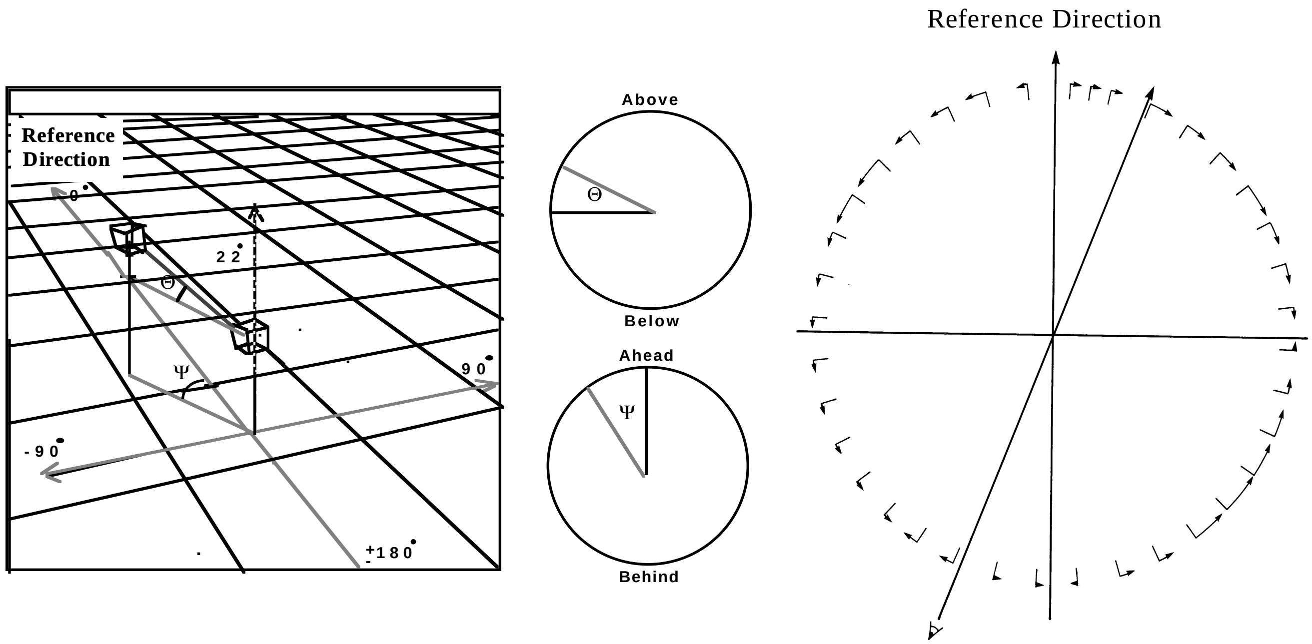


Figure 6. In order to investigate the accuracy with which viewers can recover the spatial characteristics of a 3D space projected onto a picture, subjects were asked to imagine themselves positioned at a reference cube in a picture looking along a reference direction (left image). From this position they were asked to determine the azimuth and elevation angles of a target cube positioned at arbitrary locations around them. The subjects responded by adjusting dials next to the display to indicate the desired angles. Some of the characteristic errors viewers make when responding in this manner are shown on the adjacent figure which plots the average azimuth errors of eight subjects who viewed the display from a view position to the left of the reference axis. Average errors at each of the target positions are plotted as arcs whose angular lengths are proportional to the error at each target position. The pattern of error shows a kind of compression towards the crossing axis which may be attributed to the subjects incorrect estimation of the direction of the projection's view vector.

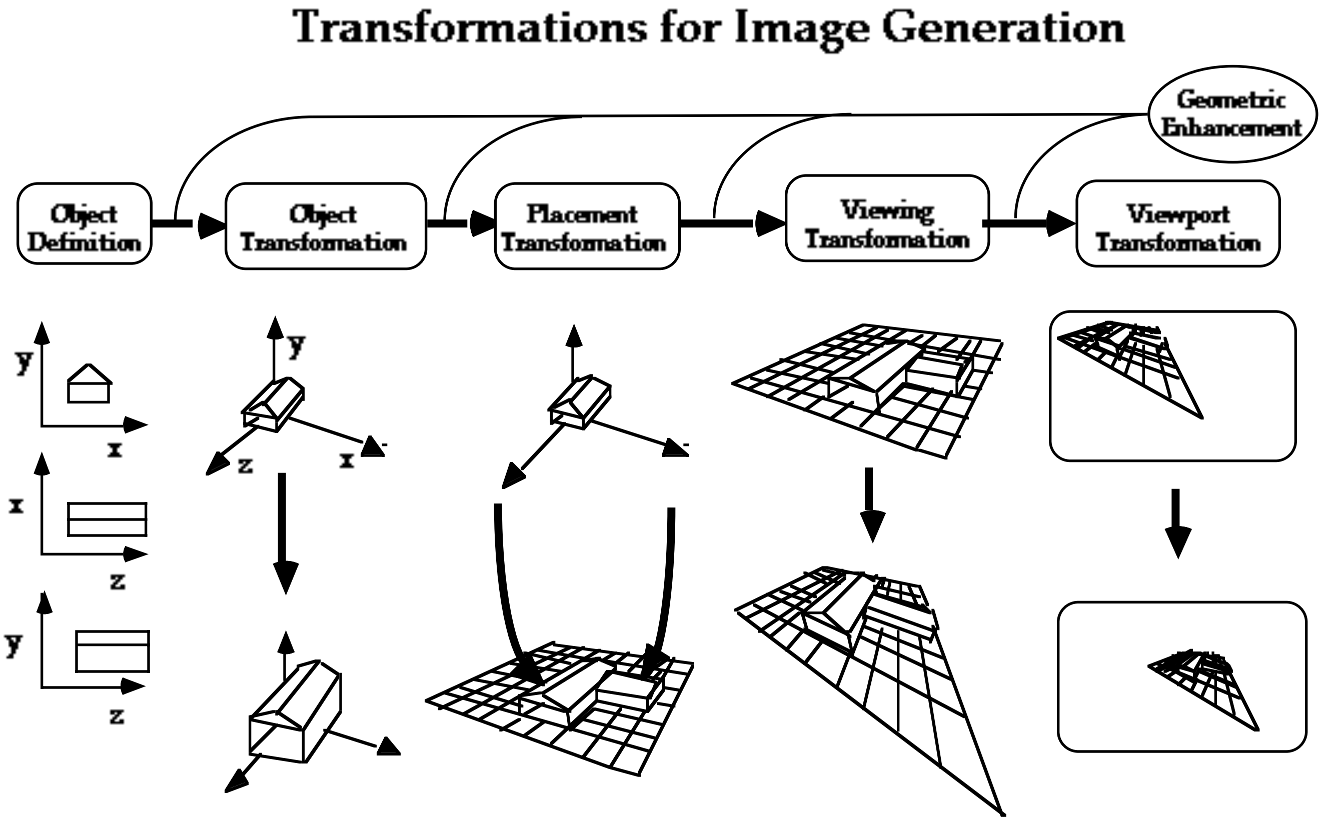


Figure 7. The process of representing a graphic object in the virtual space allows a number of different opportunities to introduce informative geometric distortions or enhancements. These may either be a modification of the transformation matrix during the process of image definition or they may be modifications of an element of a model. The matrix element or shape of the model part may be controlled externally by an independent variable or one slued to a mouse or other input device. These interventions may take place 1) in an object relative coordinate system used to define the object's shape or 2) in an object transformation, or 3) during the placement transformation that positions the transformed object in world coordinates, 4) in the viewing transformation or 5) in the final viewport transformation. The perceptual consequences of informative distortions are different depending upon where they are introduced. For example, object transformations will not impair perceptual stability in a head-mounted display whereas manipulations of the viewing transformation will.

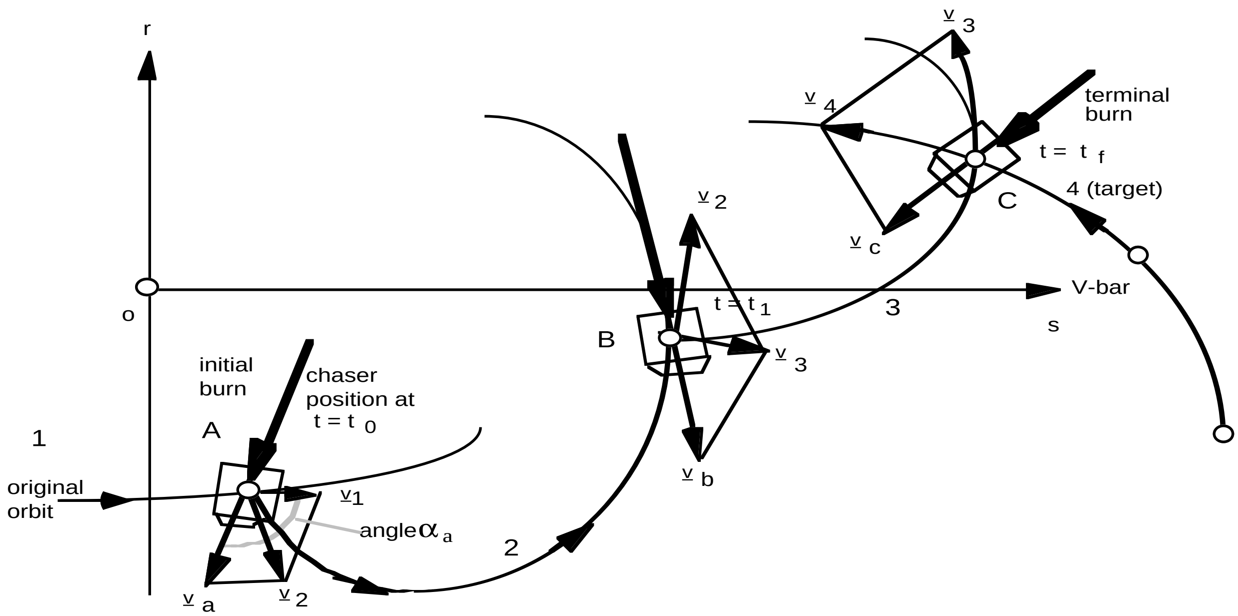


Figure 8. The relative motion for a spacecraft making a 3 burn orbital maneuver beginning with position A at time t_0 and an initial relative velocity $\underline{v}_1$. The earth is down and motion is to the right. In this case the relative position and velocities of a way-point B at time $t = t_1$ can be computed. However, a change in the magnitude or angle of the maneuvering burn at $t = t_0$ will cause a change in the direction and magnitude of the relative velocity vector $\underline{v}$ at $t = t_1$. As a result, the position of the next way-point at time t_1, will change in a nonlinear way complicating trajectory planning. In fact, in the moving and rotating coordinate system in which astronauts must operate, the apparent motion of spacecraft changes in counterintuitive ways. Forward thrusts, for example, produce upward and then backward motion! These difficulties are moderated by giving the operator direct control over the position and relative time of way-points rather than the magnitude and direction of the burn. The inverse method by which this is accomplished computes the magnitude and direction of the burn required to bring the spacecraft from the initial location $\underline{x}\ t_0$ to the way-point $\underline{x}\ t_1$ at $t = t_1$. The operator commands the position of a way-point by means of an controller such as a mouse while the algorithm "tracks" the commanded way-point by continuously making appropriate adjustments both in variables v_a and α_a.