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Research Article

A geographical information system for a GPS based personal guidance system

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Abstract. This paper describes the process of building a GIS for use in real time by blind travellers. Initially the components of a Personal Guidance System (PGS) for blind pedestrians are outlined. The location finding and database components of the system are then elaborated. Next follows a discussion of the environmental features likely to be used by blind travellers, and a discussion of the different path following and environmental learning modes that can be activated in the system. Developments such as personalizing the system and accounting for veering are also presented. Finally, possible competing schemes and problems related to the GIS component are examined.

1. Introduction

In a previous article we discussed some elements of a geographical information system (GIS) that could act as a database and analytical tool in a Personal Guidance System (PGS) for blind and vision-impaired travellers (Golledge *et al.* 1991). Over the past seven years considerable changes have been made in the nature of the guidance system. In particular, the spatial database and analytical functions that are crucial to the traveller's successful use of the virtual acoustic interface have been modified. As computational and satellite tracking technology have advanced so too has our equipment evolved (e.g. computer miniaturization and portability). Changes to the PGS now allows the assumption of a naive traveller who is not experienced with GIS or any other technology used by the system. It is therefore a practical example of a 'naive GIS' (Egenhofer and Mark 1995).

The primary purpose of this paper is to update the description of the PGS and to focus on the problem of building a database and a set of GIS functions that can be accessed in continuous real-time by a naive traveller moving through an unknown environment. Real-time access is essential because, as will be explained in a following section, the unique component of the PGS is that environmental features identify themselves via a virtual acoustic display when they are within the vicinity of a traveller, thus giving enhanced information about the non-visual environment through which locomotion takes place. For a sighted traveller this might be a description of what's in a parallel city block; for a vision impaired traveller it could include what is currently nearby. This in turn impacts on the richness of the traveller's cognitive map, and influences his/her ability to determine location, orientation, course, and frame of reference. In addition, the spatial layout of local and distant environmental features is provided. Significant problems that had to be overcome are discussed as are current and future problems that may limit the effectiveness of the proposed guidance system unless innovative research produces timely solutions. The first section consists of a brief description of the components of the Personal Guidance System (PGS), so that reasons for choosing certain options for the spatial database and GIS are made transparent.

2. Overview of the Personal Guidance System

The guidance system consists of three modules (figure 1). A complete description of the system design is provided in Loomis *et al.* (1994). Details of the system hardware are provided in Loomis *et al.* (1995).

The first module concerns User Location and Orientation. Following suggestions by Collins (1985), and Loomis (1985), a Global Positioning System (GPS) receiver with differential correction (DGPS) is used to determine location and to track the path of travel. The current version includes a 12-channel receiver from Trimble Navigation (Model 4000SE) running ProPlan software. Differential correction can be obtained from a commercial service (e.g. Accqpoint) which uses a base station in the city of Santa Barbara (located about 20 Km away from the test site). An alternate differential correction can be obtained from Coastguard stations spaced around coastal USA. The GPS and FM radio receivers are carried in a backpack also containing a sub-notebook computer (figure 2). The computer in use is a 486-25 MM2 subnotebook computer with a hard disk. The DGPS configuration gives an absolute positional accuracy on the order of 1m root-mean-squared error, under conditions of good satellite availability.

The other component of this first module is concerned with the traveller's orientation (heading or facing direction). Although GPS can indicate the traveller's course (direction of travel over the ground) on the basis of successive position fixes, navigation systems are more effective when heading is independently available, for travel instructions are usually expressed relative to the traveller's heading rather than course, and course is not defined for a stationary traveller. In the PGS, heading is indicated by a fluxgate compass mounted on the strap of the headphones worn by the traveller; as such, the compass indicates orientation of the head rather than the body. Head orientation is measured because the virtual display component uses head orientation to compute the proper directional cues for spatialization of sound.

The GIS Components Module includes a digitized base map and software designed to track the traveller's path, select routes, advise the traveller about landmarks and local features, control dynamic access to the database, and correct for signal loss or error. It also contains the commands needed to assist navigation.

In standard GIS, sets of spatial or non-spatial attributes are tied to geocoded locations. Spatial attributes might include some measure of system centrality, con-

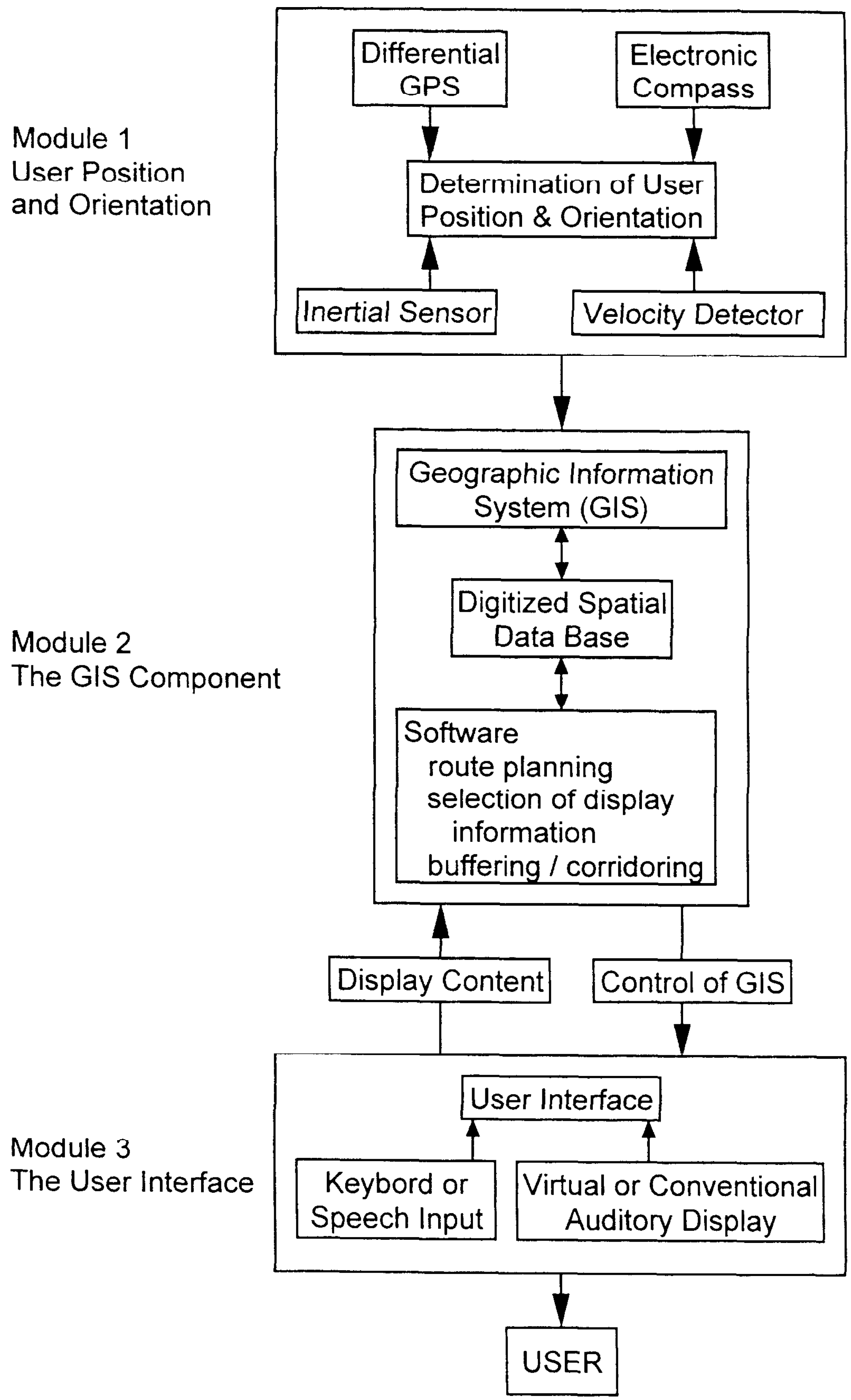

Figure 1. Guidance system consisting of three modules.

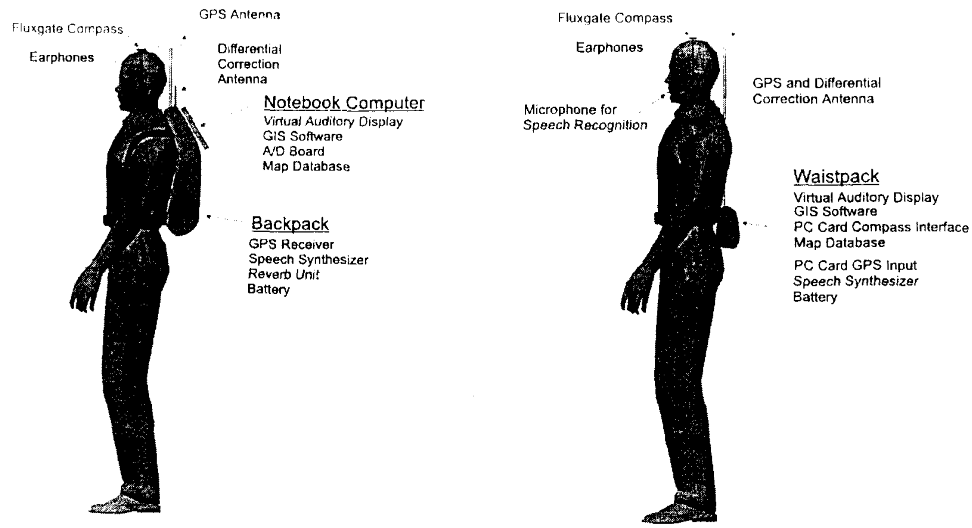

Figure 2. (a) Current configuration of PGS. (b) Planned configuration of PGS.

nectivity, size, area, feature or population density (if the location is, say, a mean areal center representative of a census tract), distances to other features, nearest neighbours, and so on. Many of the attributes stored in commercial databases have limited relevance for blind people, particularly in relation to travel. Information such as location of transit stops, whether or not a shelter is present, proximity and direction of the nearest intersection, whether the intersection has a traffic control system or curb cuts, or how far a bus stop is from a corner, are more important to blind travellers than cadastral features such as parcel size, planning features such as age of nearby buildings and number of occupants, or design features such as colour, number of rooms, or age of building (Strelow and Brabyn 1982, Rieser *et al.* 1996). Attributes useful for blind navigators include building frontages, road characteristics such as direction of flow or existence of a central divider, parks or open areas, bicycle lanes, car parks, or other types of land use.

Given the need for operating in real time, and because of size constraints imposed by the backpack system design, which places limits on data storage and manipulation space, only a limited number of GIS functions have been incorporated in the PGS. In particular, use is made of functions for buffering, centroid calculations, a path selection algorithm, and various procedures for calculating distances and directions. Buffering and corridoring may need further definition here: buffering is the selection of data from the GIS that pertains to the space immediately around the traveller; this information becomes available for display. In the PGS, a 30 by 30 m buffer is the default option, but its size can be manipulated (at this stage) by keyboard input. The initial buffer is centered on the traveller's location in the database. Within the adjacent area covered by the buffer, features or objects represented in the database are scanned for importance weights (e.g. a nearby on-route building may have a prior weight of 1 (most important) allocated to it; an off-route bench, tree or telephone booth may have a weight of 3 (least important)). The traveller can identify what level(s) of salience will be attended to, and the appropriately weighted features will be identified by name as they fall within the buffered zone. The location of the buffer remains constant until the traveller reaches a set distance from the buffer boundary (e.g. 7 m). At this time the old buffer disappears and a new one centered on the current location of the traveller is created. Thus some information activated by the old buffer is deleted, those features still covered by the new buffer are retained, and additional appropriately weighted features located within the range of the new buffer boundaries are added. This regular shift of the buffer continues as the traveller follows the chosen route (figure 3). A narrow corridor (approximately 4 m wide) containing the path to be followed also is defined; if the traveller veers beyond this corridor an error is signaled, and directions are given to the traveller to return to the path.

The User Interface Module provides for two-way communication between the GIS and the user. There are two display options for GIS-to-user communication: conventional speech display through a speaker or earphone, and a virtual acoustic display using binaural earphones. The conventional speech display is the alternative that all other groups developing navigation systems for the blind have adopted (e.g. Fruchterman 1995, Gill 1996, and Makino *et al.* 1996). When using the PGS, information about the environment is conveyed by synthetic speech. The synthesized speech signal is the input to an Alphatron virtual acoustic display, which outputs binaural signals to the earphones worn by the user. The virtual acoustic display allows features to 'call' as if from their real location in objective space. Output consists of spatialized synthetic speech in which both virtual beacons along the route and virtual landmarks off-route identify themselves by name. A full description of the virtual auditory display originally developed for this project is given in Loomis *et al.* (1990).

In the long run, operating commands will be given by direct speech. At this time interaction is via a 24 button key pad. This controls commands to set up and operate the system, choose the guidance mode, actuate buffers, and select the mode of operation.

The largest design constraint is that the system must operate in real-time on existing (portable) computer hardware. Initially we used an 80486, 25 MHz sub-notebook computer. Miniaturization of the system is planned for the future. The design constraint was met using a simple time-sharing scheme to allocate resources among the different sub-systems. The highest priority was given to updating the virtual acoustic display, as the accurate portrayal of a virtual sound source requires updating for any changes in the observer's orientation. A high priority was also given to processing information from the GPS receiver.

The Trimble hardware handles all computations necessary to find user position from the prevailing satellite constellation, including the integration of differential corrections. Originally purchased from a commercial company (Accqpoint), corrections can now be supplied by a US Coast Guard network. Communication between the Trimble receiver and sub-notebook is over a serial line at 9600 Baud. Communication is defined by the Trimble Serial Interface Protocol, TSIP. The GPS receiver is configured to transmit current position to the computer as soon as available and to notify of any changes in satellite configuration or availability of differential signal. Queries to the receiver can also be made for any other receiver parameter. This information can be, when desired, written to logging files. The timesharing between sub-systems is such that after processing any bytes held in the serial port buffer, control is passed on to the other sub-systems. When a complete packet of location and error correction measures has been received, the appropriate

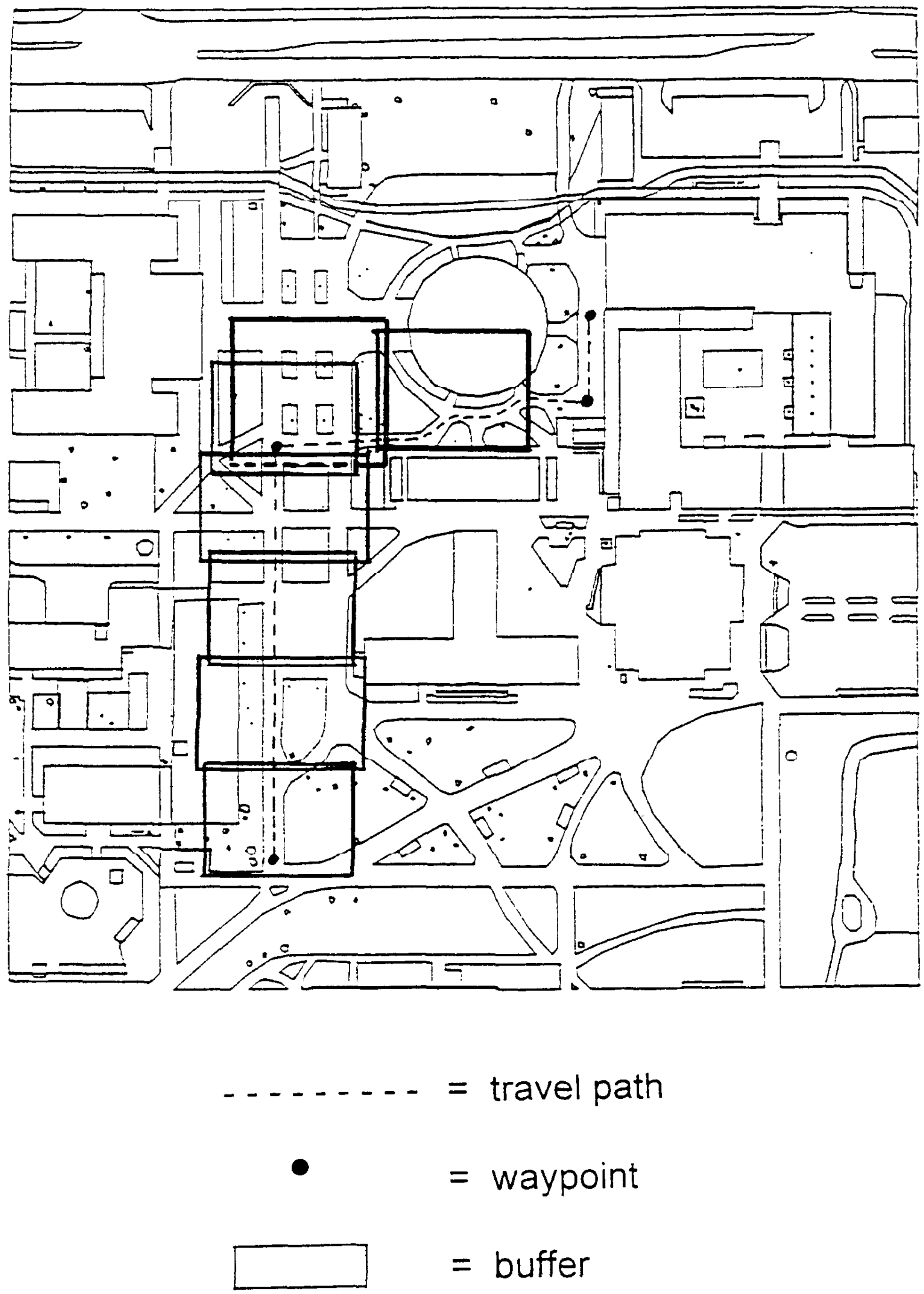

Figure 3. Map of area showing travel path and several overlapping buffers with selected layout information.

state variables are updated. Problems such as signal loss or reflection are discussed in a later section.

2.1. *Comparison to other systems*

As we envisage it, the PGS is a true navigation aid. It also provides information about the proximate and the more distant and occluded environment. This enriched source of information should give to the vision impaired or blind traveller capabilities similar to that available to the sighted traveller who, while walking, glances in various directions or who looks at a map, and from this visual scanning, determines what features are close and distant. Thus it is designed to go well beyond the concepts of other electronic guidance systems, although the ultimate success of the PGS will depend on the successful testing of the software functionality built into the system. Some of this software is still being developed, and testing of its performance is still ongoing. Other guidance systems (e.g. Arkenstone's STRIDER, Fruchterman 1995, the MoBIC Guidance System, Gill 1996, and the GPS Cellphone, Makino *et al.* 1996) use GPS to locate an individual, then provide the traveller with verbalized route related information. Such information relies on the traveller's confidence and independence, and his or her knowledge of the major local geographical frame of reference. It also relies on being willing to accept the limited information contained in the verbal commands as sufficient for goal achievement. Existing systems differ in the extent to which they can provide orientation information.

Without proper orientation (e.g. carrying a separate compass), significant errors can be made in determining geographic direction (Klatzky *et al.* in press), and no additional information is gained about the environment as the traveller proceeds along the specified path. At this time STRIDER has no compass attachment, while MoBIC suggests a compass be carried by the traveller and be worn on the body (e.g. attached to a jacket lapel). Such devices are really path following supplements rather than navigation or environmental learning assistive devices.

It is doubtful whether the sparse information provided in the verbal descriptions used by these devices would be of much help in understanding the complex locational configuration of features in a real world environment. Indeed recent research by Taylor and Tversky (1994), Ferguson and Hegarty (1994), Franklin (1996) and Couclelis (1996), points to the difficulties of interpreting spatial relations from common speech (natural language).

Although simple systems may reduce the fear of becoming lost, they may not enrich the traveller's knowledge of the environment or give to them some of the knowledge capability typically obtained by sighted travellers using a map or glancing around (Blades 1991, Spencer and Blades 1986, Ungar *et al.* 1994, Mark and Frank 1991). They may fall short of being a 'quality of life enriching device.' Similarly, since such devices lack objective orientation capability, they must rely on the traveller's knowledge of underlying geographical directionality (which is usually quite fuzzy even in people with full vision). In comparison with these systems, the proposed PGS does act as a navigation aid, not just a path following device. It also provides landmark and local layout information in the vicinity of a traveller.

Given this overview of the PGS, the next section discusses the nature, functioning, and problems associated with the spatial database and GIS that constitute the second module of the system.

3. The spatial database

3.1. *Information needed by the blind traveller*

Most existing databases have been developed without considering the needs of blind users. In particular, few if any of the databases developed for travel (usually by auto) have contained features that could help a blind pedestrian or transit user. Missing are features such as the presence or absence of sidewalks, paths (e. g. across a park area), or trails (e. g. through a recreational area). There usually is no indication as to whether or not a street has bike paths along its edges, nor are the widths of roads and the number of traffic lanes given. Other missing features include whether the traffic is one way or two way, whether there is a central divider or pedestrian island, whether there are curb cuts facilitating entry into the street (see Hauger *et al.* 1996, for an evaluation of just how effective these are), whether traffic lights or other control systems—such as stop signs and pedestrian crossings—exist at a corner, whether the traffic signals include auditory signage to indicate periods of safe crossing, and whether traffic is allowed to make u-turns (often of significant importance when trying to cross a divided roadway). Environmental features often used by blind travellers to estimate distance travelled include fire hydrants and telephone poles (whose regular spacing provide the blind traveller with a way of estimating distance travelled). Most existing databases do not indicate changes in texture of the surface being covered or on either side of it. All these features can be used by the blind traveller to estimate distances travelled, to help ensure safety when crossing streets or roadways, to obtain shelter during inclement weather, or simply to allow 'shorelining' to take place. (Shorelining involves using a continuous edge such as a wall, a curb, or a change in surface texture such as the edge of a paved path, to guide one's progress (Welsh and Blasch, 1980).)

3.2. *Early states of the GIS*

The GIS had its origins in hand digitized AutoCad maps of the UCSB Campus. As these were incomplete and inaccurate, they were corrected into ARCINFO readable coverages. The initial database was developed in an ARCINFO format. This allowed us to produce a very detailed database, extending for instance, to manholes and telephone poles. Although ARCINFO at first seemed to provide excellent software for compoiling the database and an appropriate range of GIS functions, it soon became evident that it was too powerful and too complicated (and thus too inaccessible) for use in real-time conditions. Questions that arose with respect to the large amount of detail in the ARCINFO database included: Was the level of existing detail necessary for a blind navigator? How much detail is needed to provide a reasonable knowledge of layout and significant cues and landmarks for navigational purposes? How should specific entities be represented, for example, should bike paths be lines or polygons? Did the CAD-based drawing from a 1983 air photo mosaic provide the level of accuracy needed for personal navigation purposes? For example, were the sidewalks located accurately enough for a GPS initiated trace of a traveller's movements to stay within the parameters of a particular path? Did the polygon topology exist for all the coverages required in the database? What basic coordinate system should the data be projected into? What was the current locational accuracy of the data?

To conserve waiting and processing time, alternatives other than a full-scale GIS were considered as the host for the database and auditory interface. Consequently the original AUTOCAD DXF file which described a minimal campus database was reactivated.

The current database and analytic functions were assembled in a CAD/DXF format: all programming was done in 'C'. The resulting CAD/DXF database was divided into fourteen coverages, each representing a particular theme. These were grouped into four general classes: (1) transportation (e.g. roads, bike paths, walkways, car parking areas, bike parking), (2) buildings (e.g. permanent and temporary), (3) land use (e.g. open space, recreation, vegetation), and (4) other objects (e.g. light poles, telephones, stairs). Each coverage consisted of a layer of chains that defined the areas of the features enclosed. For example, the building coverage included chains that enclosed polygons which defined the footprint of each building. One of the limitations of CAD-based systems is that attributes must be stored as separate disk files. But given the CAD/DXF constraints, there were no attributes or lookup tables describing the features of individual buildings. These fourteen coverages were simply the original converted AUTOCAD files edited to eliminate digitizing errors.

3.3. *Current GIS: CAD/DXF format*

The new system had to be expanded so that some basic GIS functions could be embedded within it. A fundamental set of functions useful for most GIS has been suggested by Albrecht (1995). Basically, functions built into the new system were similar to sets of cognitive functions performed by travellers when learning a new environment. Examples are given in table 1. Typical functions include distance and direction estimation, scale transforms, orientation, and interpolation.

A polygon format for data encoding was chosen whenever possible. For example, kiosks, manholes, planters, and conversation pits were coded as small polygons. More important, however, was polygonal coding of sidewalks, bike paths, service roads and other roads. This format was chosen because of the difficulty in differentiating which was the real path for travel in cases where bike paths paralleled sidewalks

Table 1. Selected functions common to GIS and spatial cognition.

Location of points	dispersion
Interpolation	connectivity
Line drawing	mean areal centre/centroid
Line length estimation	modifiable areal unit/regionalization
Search	perimeter, height, volume
Buffering	shape
Corridoring	similarity
Overlaying	measurement
Area (polygon) definition	decomposing
Slope and aspect	scanning/digitizing
Viewshed, line of sight	georeferencing (encoding)
Network structure	rubber sheeting
Shortest path	generalizing/smoothing
Abstraction	enhancement
Proximity	aggregation
Nearest neighbour adjacency	scale change
Diffusion spread	filtering
2-D surface interpretation	boundary definition
3-D surface interpretation	data retrieval (decoding)

Source: Adapted and enhanced from J. Albrecht (1995) 'Universal GIS operations' Ph.D. Dissertation, Department of Geography, University of Vechta, Germany, pp. 15–20.

and sidewalks paralleled and 'merged' into building walls. Although coding both the edge of the sidewalk and the side of the building with parallel lines introduced a small location error into one feature or another, it was preferable to having the sidewalk defined only as a single line feature which might end at a building edge and produce confusion when the computer attempted to differentiate the two features as separate entities as needed for specifying a path to be followed.

While the extremely detailed campus database on which we initially worked could be justified in terms of the amount of detail that a blind person might require in order to travel safely, independently, and in a relatively obstacle-free way (Golledge 1991), upon reflection, many of the layers appeared to be unnecessary. Maybe in the future, with proper computing power, these could be retained, but based on accumulated knowledge of the techniques of blind travel, many features and levels were eliminated. For example, surface type may be unnecessary because a person travelling with a cane or a guide dog can quickly determine the type of surface upon which he or she is travelling. The long cane specifically picks up variations in surface texture such as the differences between a surfaced path (e.g. cement, brick, tile, or bitumen walkway) and an unsurfaced path (e.g. packed dirt, grass, or other type of natural surface) (Blasch *et al.* 1996). Similarly, since travel would rarely be across unsurfaced areas with different types of natural vegetation, detailed vegetation layers proved to be unnecessary, and a simple indication of whether an area was vegetated or not proved satisfactory for the most part.

Future versions of the guidance system might include an ultrasonic obstacle avoider, supplementing or even supplanting the blind traveller's own use of cane vibrations or echo location; this would reduce the need to store many detailed geometric elements. The addition of such an obstacle avoidance system should reduce the need for frequent updating of the database, for many of the most frequently occurring obstacles to the blind traveller are temporary environmental features (e. g. construction barriers or excavations, temporary diversions, randomly placed waste bins or outside furniture, and so on). An environment in which complementary travel aids were available, such as Verbal Landmarks (for building directories), or Talking Signs® (e.g. for identifying key intersections or other environmental features,—see later section on non-GIS travel aids), would reduce the need for encoding small scale geometric features such as waste bins, signposts, permanent seats/benches, planters, kiosks, elevators, or stairwells.

3.4. *Map registration*

The map was registered by locating a GPS base station at its correct position on the map. Initial scaling of the map was accomplished by measuring the physical distance between several map features (in both x and y directions). The map was scaled in AUTOCAD until the distance between those features corresponded to the physical distances. To confirm the scaling, a GPS logged path, which covered a large portion of the campus, was overlaid on the map (figure 4). The path was considered stable with respect to latitude and longitude because it was the average of several traversals all with differential GPS correction operating. The initially scaled map based on a primary registration point did not fit well, and was re-scaled to fit the GPS located path.

4. Operating characteristics of the PGS

In the following sections a discussion of the operating characteristics of the PGS is provided. Initially, an emphasis is placed on how the database is partitioned for

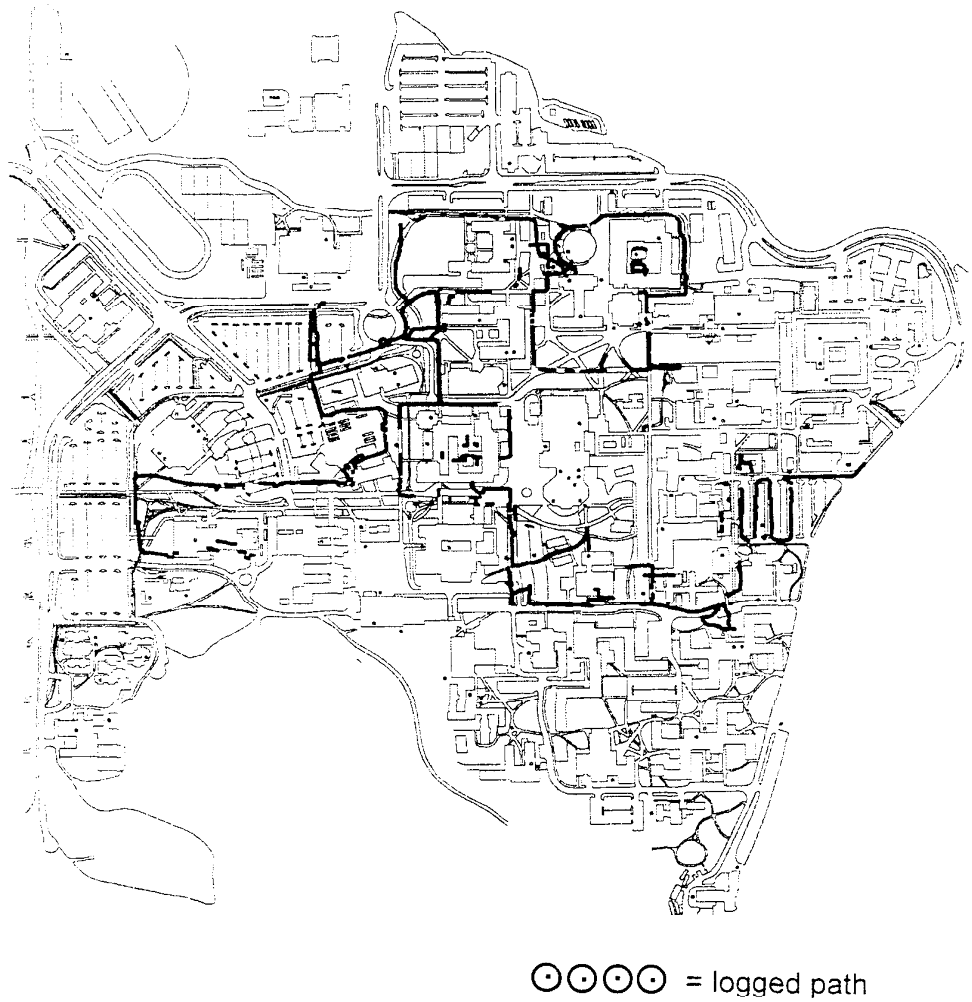

Figure 4. Map of GPS logged path.

timely access, and the command structure is described. Then follows a summary of how the PGS works in terms of path selection and path following. In particular the use of corridoring to maintain contact with a given path and the use of buffering to identify relevant nearby features are explained.

4.1. *The impact of partitioning and segmentation*

Due to memory limitations associated with running under DOS and the time consuming nature of disk access, the entire map was partitioned into a spatial quadtree. The partitioning process began with a two-dimensional bounding box which enclosed all map entities. This box was subdivided into quadrants. DXF files were then created, into which were placed the map entities contained by each of these smaller bounding boxes. Containment by a bounding box was decided based on the entity centroid (i.e. if a building overlapped two bounding boxes it was allocated to the one containing its centroid). A running count was kept of the memory necessary to store a partition's entities. If a partition exceeded a set size criterion, its bounding box was subdivided and its entities were re-partitioned. The process thus created a quadtree with variable size leaves. A description of the final partition files was stored for future map access.

Upon activating the system, the decision as to which leaves are to be loaded is based on the proximity of the traveller to the centroids of the bounding boxes. To determine when to re-configure the loaded partitions, the user's position is compared to partition boundaries. When the leading edge of the buffer around the traveller approaches the edge of a partition, that new partition is loaded. This new partition covers the subsequent segments of the path. At the time of reloading, objects from the new partition enter the buffer.

Access to a larger address space would make feasible a RAM-based version (cf. disk based version) of the above partitioning process. Then the map information common to all partitions could be stored as the environmental base and a spatial quadtree could be constructed in memory. The granularity of the spatial quadtree would be based on machine performance criteria, such as the amount of time to access all entities in a given leaf.

4.2. *Activating the PGS: waypoint versus spatial lead*

Procedurally, the traveller starts by activating the GPS locator, establishing the buffer to define a set of proximate objects, and defining the type of mode to be used (e.g. waypoint or landmark layout mode). If waypoint is selected then, upon entering the location of a destination, a path selection algorithm determines the first waypoint. As movement along a path segment occurs, the waypoint calls its number, increasing in sound level as the traveller approaches it. Once this goal is achieved, it is acknowledged (i.e. 'reached waypoint *x*') and the next waypoint beacon is activated. The traveller orients on the new directional label and proceeds along the next path segment. As travel continues, and if a 'layout' mode is chosen (see §5 for elaboration), the proximate objects are identified to the traveller. As the traveller approaches the buffer's boundary, a new set of proximate objects is determined.

One way to guide the traveller from a well known or well used starting point to a known destination using auditory cues from virtual locations is to 'hardwire' several 'paths' in the environment and lead the traveller along the path via sequentially numbered virtual beacons. By orienting on and pursuing each beacon in turn, the traveller is guided from waypoint to waypoint. Such paths might represent habitually travelled routes which are followed almost invariably (e.g. journey-to-work, journey-to-buy food, or other highly repetitive activities (Axhausen and Gärling 1992). These paths are constructed from a number of 'waypoints', which are locations along the path at which the observer is required to change the direction of travel. The waypoints are numbered consecutively from start to finish. The traveller, originating at waypoint 1, walks to each of the successively higher numbered waypoints, being guided by the directional auditory cue of the current waypoint speaking its numerical value. Normally one waypoint automatically switches to the next higher numbered one when the traveller arrives near it (i.e. within a 5 foot radius). But, manual switching to another waypoint on a given path is also possible. This powerful alternative allows the blind traveller to take a shortcut to a distant waypoint along a path, an act which few if any blind travellers have been able to do prior to this development because of uncertainty about possible alternate paths. An example might be to shorten a regularly followed sequential 'U' shaped path by manually requesting a direct (beaconed) route between the two end points. At any time it is possible to enable or disable paths or waypoints and to add or delete items from the speech output (e.g. to replace a simple number designating a waypoint with a number and building name).

An alternate path following mode, called spatial lead, is to project a virtual acoustic beacon at a standard distance (e.g. 2 m) in front of the traveller. This beacon follows the path to be taken and leads the traveller along each segment. It clearly identifies direction changes and provides continuous movement potential rather than waiting for the next waypoint to be activated and making the appropriate course change. This mode has advantages for travelling curved pathways, because the spatial lead circumvents any tendency to stray from or straighten the curved path.

4.3. *The problem of wandering from a path*

One of the problems of walking without sight is the tendency to veer from a straight line (Worchel 1951, Cicinelli 1988, Loomis *et al.* 1993, Guth and LaDuke 1994, 1995). This could cause some problems, especially in those segments where the GPS signal might be lost because of interference. To address this problem, the GIS notion of corridoring can be used. Essentially, a corridor of arbitrary diameter (e.g. 3 m) can be defined about the centre of a line of travel between consecutive waypoints (figure 5). As long as the traveller stays within the corridor so defined, there is no interruption in the presentation of auditory information including the virtual beacon and the announcement of labels of those features contained within the buffer zone. However, if substantial veering occurs and the traveller transgresses the corridor boundary, buffer operations are suspended and an audible warning ('path') is heard. The traveller is then reoriented to the direction of the 'path' sound, which returns him or her to the nearest point on the original path, using right angle offset procedures.

However, some problems can arise when the traveller both transgresses the path and loses the GPS signal at the same time. Disorientation can occur and failure to return to the original line of travel is a possibility. To overcome possible disorientation (e.g. a 180 degree reversal), the suppression routine can be modified by interspersing the virtual beacon sound intermittently between the off-path auditory indicators. Thus, instead of just hearing 'path, path, path....' until recovery occurs, the traveller hears 'path, waypoint, path, waypoint, etc.' This means that orientation to the waypoint controlling direction of travel can be maintained and that travel may be continued without fear.

4.4. *Route selection*

The route selection algorithm used is a modified Dijkstra shortest-path algorithm (Yang 1991). Once an origin and destination have been determined, it begins searching for possible routes according to a shortest path constraint. If more than one route is found (e.g. as might occur between diagonally opposite corners of a regular grid), a route using fewest turns is given the highest priority for selection.

5. Learning the environment: Landmark and layout modes

Navigating a predefined or novel-path by following a spatially lagged virtual beacon provides an easily comprehended and cognitively simple way of travelling independently. However, using such a guidance mode still leaves a blind traveller unaware of nearby or distant on and off route features. Both landmark and layout

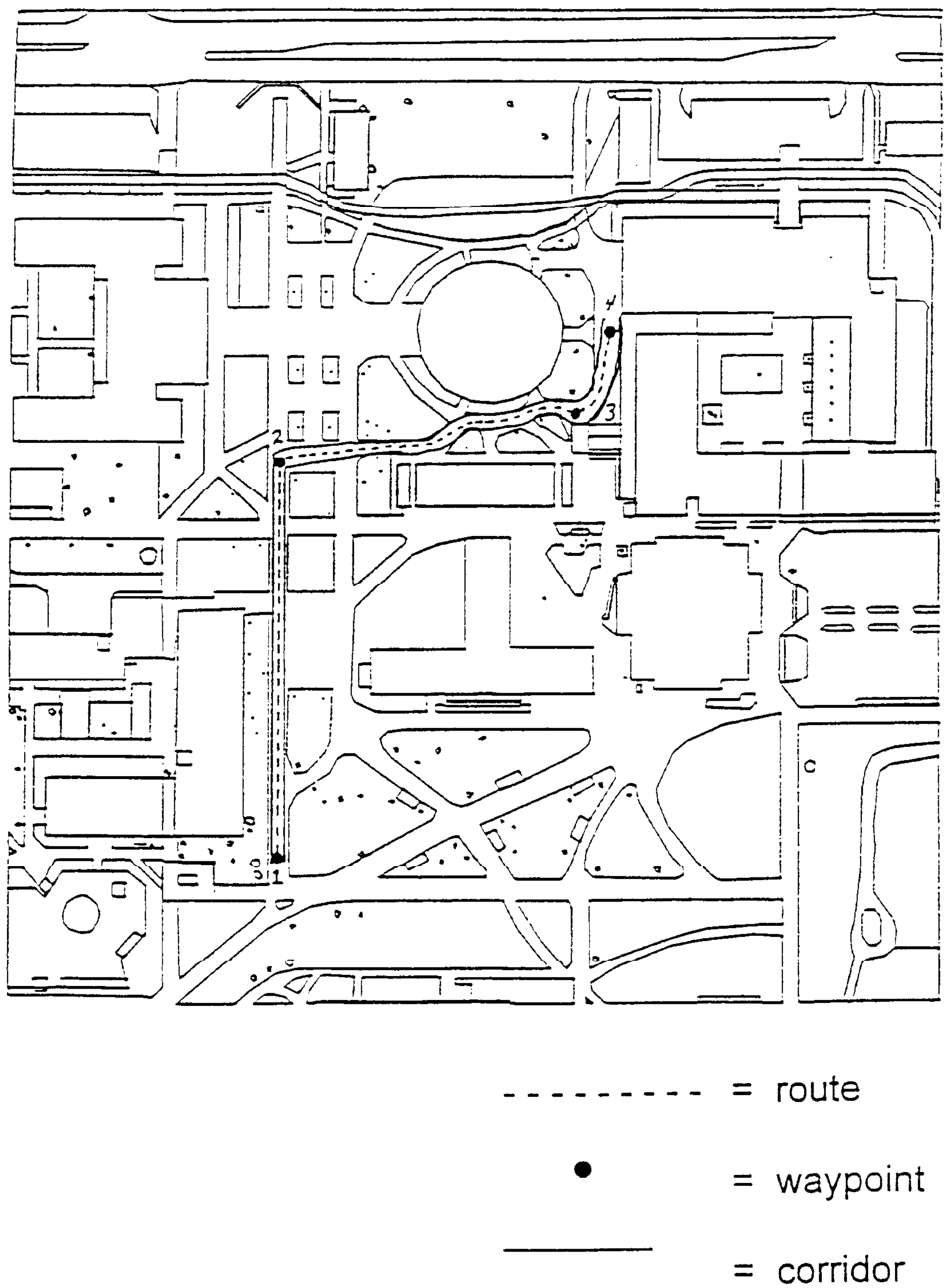

Figure 5. Example of a 3-leg path plus corridor.

modes provide a means for learning the local geography of features. Since the usual practice of Orienation and Mobility training is to teach routes rather than layouts, the PGS provides an opportunity for the blind traveller to engage in 'configurational' or 'layout' learning. Often called 'survey knowledge', this is accepted to be the highest level of spatial learning (Siegel and White 1975, Piaget and Inhelder 1967). But without the use of vision, this requires complex internal integration of routes into networks and configurations; tasks that those without vision are rarely trained to accomplish.

Two modes of representing configurational information about environmental features are used; landmark and layout modes. Both modes use spatialized sound to localize entities within the environment, thus providing the auditory equivalent of a vision-based 'survey' representation.

5.1. *Landmark mode*

Landmark mode may be used most often by an experienced traveller who knows a route and its nearby features well. Such a traveller may only require an occasional check on current location with respect to well known distant places to gain reassurance that the correct direction is being followed, or by triangulating on two or more landmarks, to use mental geometry to estimate approximate current location. This mode's primary purpose is not to facilitate environmental learning, but to help estimate current location and heading. It serves a similar purpose to the head turning and visual scanning for well known features that is typical of sighted travel.

As with sighted travellers, landmarks often play an important part in wayfinding by those who are blind or vision impaired and in facilitating knowledge of location and orientation (Lindberg and Gärling 1982, Evans *et al.* 1984, Presson and Montello 1988). In landmark mode, only features in the database that have been identified *a priori* as having a given importance value are activated (at this time only three levels of importance have been designated). Two orders of landmarks are defined: 'system' landmarks that generally are recognized as dominant local features, and local landmarks (called 'nodes' by Lynch, 1960), which are nearby features of some importance to be activated when appearing in a buffer and given importance ratings of 2 or 3. Features given an importance level of 1 are the most commonly identified and most familiar landmarks in the larger scale environment. These could be the same places identified by sighted people. Accessing these distant landmarks (something that is virtually impossible for blind travellers to do under normal conditions) gives the blind traveller a larger scale frame of reference and the ability to determine his/her approximate current location within that geographic space (e.g. by triangulation procedures). It may also help to identify the most familiar frames of reference, whether they be the cardinal compass directions of geographical space (north, south, east, west), or a more local relational frame of reference (such as the pattern of a local street system (Presson and Montello, 1994)). If the traveller is familiar with the approximate location of these geographical scale landmarks, use of internal processes (such as mental triangulation) can provide an approximate indication of the traveller's current location.

5.2. *Layout mode*

At the more local scale, i.e. the scale of the buffer zone, the guidance system works in what is termed 'layout mode'. Once the buffer has been established around the traveller, the GIS searches it for features with designated importance levels. These are activated according to either automatic or manual commands. Layout mode provides information similar to that obtained when sighted people travelling the same route simply turn their heads and scan for significant features in their vicinity.

Users can select subsets of the currently loaded entities in several ways when they operate the system in layout mode. These include proximity to the navigator, layer in the database, or attribute value. A list based on proximity is useful for informing the user of their immediate surroundings, not only for learning layout but to warn them of possible obstacles. Because entities are linked to a simple set of attributes such as building name, size, or type, a command may be given to 'identify large buildings'. As the traveller follows a selected path, buildings that have the attribute 'large size' and that lie within the buffered area would then be identified and spoken. Similarly, one can designate that only features contained in one specific layer are activated if they fall within the buffer zone (e.g. only vegetation, only buildings).

The virtual auditory system is intended to display the spoken information so that it appears to emanate from the distance and direction that the named entity occupies with respect to the traveller's location and orientation. Environmental features that have been selected for spatialized auditory presentation can be ordered in different ways. One is by proximity to the traveller. Because the distance relations to the traveller change as he or she moves within the environment, the order of presentation and the features identified as proximal enough to be spoken also change. Alternatively, features can be spoken in order of clockwise direction; indeed one can limit the occurrence of feature names to those lying in that section of the buffer that is in front of a perpendicular to the line of travel in the forward direction.

The above constraints are default options and allow the guidance system to choose a feature presentation order automatically. However, the traveller can also have control by keypad or speech. Using the current keypad input, travellers can indicate when they want the next item in a list (which is ordered by one or another of the above rules) to be spoken. It is possible to signal a backup to hear a previously spoken item again. Clockwise or counter-clockwise ordering is possible; this may be important if the traveller has knowledge of the configuration of important features in the vicinity relative to the direction of travel. If the progression of feature announcements is halted at a particular place, the system will keep updating the position of that single feature until a new one is requested.

Layout mode gives a power to the blind traveller that is often beyond the capability of sighted travellers. If the buffer is set large enough, visually occluded features (such as those a block or more away) can be identified. Thus the *terra incognitae* of far distances are reduced to known territory. Destination substitution is possible to unseen or previously unknown places, and shortcutting becomes feasible to get to alternate destinations. In other words, activity substitution processes can become a reality instead of a distant, unreachable goal.

5.3. *The activation sequence and command structure*

The various steps involved in defining and activating information in the PGS are outlined below. Steps 1–5 define system parameters; steps 6–8 activate the system for a particular journey.

Step 1: Define and load a digital map of the task area.
Step 2: Select output interface (speech is the default option).
Step 3: Select and activate the locating mode (e.g. DGPS).
Step 4: Select 'speech name' option for each significant item in the database; once enabled, the name can be spoken as it occurs on the pathway or in the buffer.

Step 5: Select 'speech-rate' to control the time lag between the speaking of names.
Step 6: Buffer proximate objects around the traveller's position.
Step 7: Overlay the proximate environment with a larger geographical scale layout of critical landmarks. These landmarks can be enabled or disabled at will by activating a button on the keypad.
Step 8: Select a path from an origin to a destination.

In the current configuration, in which input is via a keyboard, each of the necessary commands (table 2) is activated by pressing 'Control' plus an appropriately defined letter. In the configuration to be developed for blind users, an auditory interface is planned. Specific commands would be voice trained using a speech recognition system. Spoken terms such as 'speech-rate', 'buffer size', 'landmark mode', and 'layout mode' will replace push-button controls for setting up the operating system, and specific origin and destination locations would be verbally identified as route anchors. Development and testing of the software needed for these commands is part of the next phase of research.

6. Problems with GPS/GIS

Some significant problems involved in using GPS and GIS technologies for travel guidance can be summarized as follows:

1. The Global Positioning System may be inadequate to achieve a desired degree of locational accuracy in many types of user environments (e.g. areas of high buildings or steep mountain terrain).
2. Currently there is a lack of any suitable backup devices to derive location and orientation when the GPS signal is lost.
3. An additional problem involves reflections of GPS signals from nearby structures. Reflected signals are referred to as 'multi-path'. Because distance to the satellite is computed from the time delay of signal transmission and signal reception, positions derived from reflected signals will be in error. Under conditions where the GPS receiver has line-of-sight access to the satellite, reflected signals may be ignored. It is unclear whether reflected signals are

Table 2. Example of commands.

Advance to next windowed item
Reverse order of accessing next windowed item
Waypoint name
Switch to next waypoint
Shift display
Warn of close object
Cycle through importance types
Signal north direction
Speak range and bearing of waypoint
Toggle layouts on and off
Toggle waypoints on and off
Toggle buffer on and off
Toggle to indicate range of object or distance to waypoint
Define a waypoint
Make a path out of the defined waypoints
Indicate waypoint direction

identified by the signal having the shortest path to the satellite. It is under conditions of occlusion that reflections become problematic. If the receiver is stationary, then it is possible to reduce the problem of reflected signals by setting the elevation mask. For our purposes, a mask of 35° above the horizon determines satellite selection. Direct signals at low elevations thus will be rejected. The drawback to raising the elevation mask is that it increases the positional dilution of precision (PDOP) because a particular satellite constellation could generate a smaller solid locational angle.

4. A major problem associated with the development of usable GPS is also the accuracy of available GPS signals. At a world-wide scale this may at first be achieved by removing the random error disturbance (selective availability) in the existing satellite signals — a procedure which is due to be completed early next century. Then, if there is successful integration of GPS and the former Soviet GLONASS systems, there will be approximately 50 satellites that could be accessed by GPS technology. Assuming the (undisturbed) signals from the United States and Russian systems can be successfully merged and accessed by a standard commercial GPS system, this should improve the availability of relevant satellites and diminish the danger of falling below the necessary four satellite configuration needed to get highly accurate location. However, the problem of obtaining a satisfactory GPS signal in inner city areas or in densely forested rural areas, or within significant covered areas such as airport terminals, bus terminals, or railway stations, and large shopping malls, may prove insoluble.
5. There is still a scarcity of detailed and accurate commercial databases for many countries of the world. Many of the existing databases lack information that is important to a vision impaired or blind traveller (e.g. even information as fundamental as to whether or not there are sidewalks on either side of roads).
6. Most cities require very large databases, and the storage required is substantial. This means that access time to bring up map segments after determining location from a GPS may involve significant delays.
7. The most common routing algorithm uses shortest path or shortest distance principles; it is uncertain to what extent this criterion is satisfactory for most pedestrian traffic, and particularly whether it is at all relevant for blind pedestrians. For example, Säisä *et al.* (1986) show that most pedestrian traffic is not spatially optimal in a shortest distance sense.

In such cases as described above, guidance will need to be supplemented by a local positioning system (LPS) that might use radio beacon, infrared, cellular telephone, or other types of devices not tied to a person that could help a traveller. The PGS system would be of much greater value if it could work with an LPS or Talking Signs® system (Crandall *et al.* 1995) within enclosed areas such as central business districts, airport terminals, shopping malls, rail or bus terminals.

7. Next steps

7.1. *Personalizing the database*

Transportation science has made innovative use of GPS and GIS components by assembling them in a vehicle which can travel at speed along designated streets, roads, and highways, while updating existing road maps (Bossler *et al.* 1991). This is done by recording a GPS signal at specific locations and depressing a function key to code features at that particular location (e.g. a highway entrance or exit; a bridge or overpass; or a sign). The PGS is capable of being personalized using similar procedures.

To personalize the PGS system, an individual needs only a framework database (e.g. the street system of a local area, which, for the United States, is readily available now from commercial sources such as those listed above) and software that identifies the limited range of functions relevant to the world of the blind traveller. For example, the blind traveller may wish to enter his or her home location into a commercial database—something that is otherwise very unlikely to be geocoded. The traveller may then begin to follow a familiar route around a local neighborhood and, where significant local features occur, obtain a GPS fix at that point, and depress a function key tied to a list of land use types so that a name is given to that coordinate location, making it accessible within a travel buffer on succeeding trips. Specific features include damaged sidewalk areas (e.g. tree roots or surface irregularities from vehicular traffic entering driveways), a local bus stop or bus shelter, the location of a friend's house, or a local store. In contrast with other systems being developed at this time *only the PGS* is conceptualized and designed to give the user an opportunity to personalize a database and incorporate and delete transient features (e.g. construction sites) that would otherwise be difficult to maintain in a database.

7.2. *Further development*

There are many problems to be solved and much research to be done before the product reported on here becomes marketable. Three problem domains stand out: hardware, software, and cognitive behavioural.

In the hardware domain, interfacing a sonar-type obstacle avoider with the PGS will involve complicated signal detection and transmittal. Of necessity, testing such developments will require human factors research into the way the different signals can be transmitted, arranged hierarchically in times of hazard exposure, and easily interpreted by the user. The design and manufacture of an auditory interface and possibly a backup keyboard interface needs further exploration, and should benefit from the current interest in exploration of voice interaction with computers. But the cutting edge auditory interaction software (such as Dragon Dictate or Naturally Speaking), needs considerable further work before it can be taken from the stationary PC to the dynamic wearable computer environment.

In the software domain, relevant research questions include: how can one improve data accessability from partitioned boxes? How can cross-boundary problems (such as buildings straddling two partitions) be most effectively handled? What style of communication about distance, direction, location and orientation are most effective (e.g. relative or absolute, naive or expert language)?

In the data model domain, would use of an object-oriented system (suggested to be the most 'realistic' because of its capacity to conform most to precepts of cognitive behaviour) simplify and extend the domain of empirical settings (e.g. urban databases)?

Cognitive behavioural research problems abound. How many different signals can a traveller comprehend while still being aware of normal ambient sound? Should signals from local cues be randomized or serialized? How can one design an auditory interface that explicitly includes distance effects? What type of layout (or configuration) information maximizes comprehension of the environment? What effect does scale changing or zooming have on the listener's ability to comprehend the information being transmitted?

Needless to say, most of these questions need to be solved for future use of GPS and GIS whether or not the potential users are vision impaired. The rate at which technology is evolving gives us considerable hope that many of these problems will be solved in the immediate future. Although the device as conceptualized and built is close to optimal in terms of the needs of vision impaired or blind travellers, it may not prove to be the most acceptable by this population. Some users have been worried that earphones will interfere with their normal use of sound to identify things or places (e.g. echo location). Others fail to see why layout information is needed, i.e. why route information is not enough. Perhaps a somewhat simplified version that lies somewhere between a simple path follower (e.g. STRIDER, Fruchterman, 1995) and a PGS might prove to be the most widely adopted device. Work on this technology needs to continue, for many of the problems detailed herein are specific to use by vision impaired or blind individuals, and would disappear when the device is used by those with vision. In the long run it is anticipated that the PGS will be much more widely adopted by sighted populations than by disabled populations, particularly as a locating, route selection, and environmental information device for travellers in unfamiliar areas or tourists in unfamiliar cultures. It is this conviction that the Personal Guidance Systems will ultimately be of benefit to a significantly large part of both able and disabled populations that warrants continued exploration of its potential. Along with other ongoing research on technology such as Talking Signs® (Crandall *et al.* 1995, Bentzen and Mitchell 1995, Golledge and Marston 1997), auditory/tactual information systems (e.g. Blades *et al.* 1994, Parkes and Dear 1997), and other innovative uses of GPS (e.g. Makino *et al.* 1996, Gill 1996), perhaps early next century vision impaired people will have the possibility for an enriched quality of life that includes increased measures of independence and mobility based on more complete and accurate local geographical knowledge.

8. Final comments

This paper has examined ways that GIS technology can assist a disabled group (the blind or vision impaired). Some of the major problems associated with navigation without sight include availability of information, accessibility to a surrounding environment, and independence (particularly of movement). The last decade has seen the emergence of a world-wide interest in using current technology to help this population achieve its goals of overcoming such difficulties.

Foremost among these attempts are guidance systems which include both navigational or wayfinding advice, and information about the environment with which one is interacting. Stationary systems such as talking signs, verbal landmarks, bar code readers, stationary radio transmitters, and so on are being used in innovative ways to provide localized on-site information to the traveller. However, they provide neither navigational assistance in the larger environment, nor general layout information such as would be equivalent to what a sighted person could access by looking at a map or by scanning a city from a lookout point. These technologies, however, have potential for use within enclosed environments such as air terminals, shopping malls, large industrial or institutional complexes of buildings, and transit terminals for rail or road vehicles. It is precisely in these areas that the GPS based system is currently at its weakest.

All of the systems have specific disadvantages. Some of these are external to the device (e.g. GPS accuracy, commercial database adequacy) and some are internal to the device (e.g. directional or non-directional information, and natural or technical language based instructions). Many of the problems associated with adopting and using guidance devices have been discussed in this paper. Not the least among these is that of the legal responsibility of the seller. Obviously environments change, many of them quite rapidly, and maintaining an up-to-date computerized database may be an extremely difficult procedure. Such would be required if the claim was to be made that a true guidance system was being marketed. And finally, readers are advised that, while the basic software needed to run the system exists, some of the software needed for embellishments (e.g. peronalizing the database, and full speech interaction with the PGS) are still under development.

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