DESIGN of COMMERCIAL AUTONOMOUS SERVICE ROBOTS

Author: V. Burhanpurkar, Cyberworks Inc.
31 Ontario Street, Orillia, Ontario. L3V 6H1. CANADA Tel. (705) 325-6110

The Goal

One of the great dreams of mankind has been to create machines in his own image. The development of such a machine, a truly autonomous intelligent robot, has long remained however, a science fiction dream. The robots which appeared on the scene in the late fifties were not robots at all in the romantic sense of the word. They were preprogrammed, non-intelligent machines which continuously performed a simple operation over and over in an unchanging environment such as an automobile factory. These robots had none of the qualities we associate with human intelligence such as the ability to sense their surroundings, move about a building, react to new circumstances, make decisions about their actions without human programming, perform a useful task (such as cleaning) without instruction and autonomously adapt its work habits to changes in the work place.

The evolution of truly human scale robotic systems will have been realized only when such machines are capable (on a task specific basis) to engage in complex operations with the same degree of a priori domain dependent teaching as a human counterpart. For example, in the case of the building cleaning services industry, once a new employee has been taught the fundamentals of the cleaning operation, he is able to walk into any new building and without any additional teaching, service that building in a logical methodical manner by correlating real time sensory data with his expert knowledge base of the fundamentals of effective cleaning. This kind of "human scale" autonomy has been the goal of Cyberworks research.

More specifically put, in the context of mobile robotics the term "autonomous" implies a robot ideally capable of executing a predefined (but) generalized task (such as finding the optimal path to roam through the corridors of a building) without being preprogrammed for the specific details of the task or receiving any instruction concerning the geometry of the domain beyond that which would be required by a human counterpart. Further, in order to effectively emulate a "human scale" level of autonomy, the robot must be able to appropriately react to unpredictable dynamic events such as moving people, new furniture, potted plants, trolleys, etc. True human scale performance further precludes the use of embedded cables or reflective lines in the floors, or the use of triangulation landmarks (reflective beacons) inside the rooms of a building. In order to achieve this level of autonomy the robot must self define its operating domain and reliably locate objects within that domain regardless of size, shape, material composition or colour. It must collect and process data in real time so as to generate navigation ideas optimal for the specific situation in which it finds itself at any given moment. It must perform these abstract functions efficiently, quickly, economically and without human preprogramming, instruction or involvement either prior to, or during the execution of the task.

In contrast to the stated ideal objective however, the bulk of current research continues to focus on techniques involving the entry of an a priori domain map into the mobile robot's memory either by down-loading from a human-entered drawing or by remote-control guidance of the robot in "TEACH" mode through a domain in an effort to either allow the robot to store a map of what it sees or to enter a "path description" by memorizing a map of the initial route. In the former case, the presence of an "ideal" vision or rangefinding device is assumed for the mapping of the domain. The second phase of this technique involves the execution of algorithms which generate optimal trajectories through the domain in memory to reach positions defined by an expert supervisor module. The third phase involves the modification of the theoretical trajectory to account for the introduction of new dynamic elements into the domain and trajectory errors due to generic slippage-type problems.

In general, these techniques have proven expensive due to computational and vision requirements and non-ideal from an autonomy viewpoint. Further, they do not readily lend themselves to alternate applications such as building cleaning or outdoor navigation where domains change daily.

In broad terms, the present state-of-the-art must be superseded by research aimed at greater levels of autonomy and visual and computational efficiencies to achieve real-time domain assimilation and task planning/execution while maintaining the realistic cost/performance ratios associated with present conventional technologies. The Cyberworks research is an attempt to reach these idealities.

System Architecture

To achieve the dramatically enhanced levels of "human scale performance" outlined above, two fundamentally novel methodologies for remote sensing and data interpretation were adopted very early in the research.

The fundamental requirements for the remote sensing system were:

a) very low cost
b) very high immunity to ambient noise
c) very high sensitivity
d) immunity to signal loss due to angle of incident, material composition, colour, etc.

Camera vision systems met all requirements except the first. However, since the ultimate aim of the research was commercial viability, this approach was abandoned. Similarly laser imagers fulfilled all but the first objective and was hence also discarded (note however, that both camera vision and laser systems continue to be a focus of advanced research at Cyberworks for special applications).

Convention ultrasound techniques met the first requirement but required significant development to fulfill the remaining requirements. Utilizing novel digital filtering techniques virtually absolute immunity to ambient noise has been achieved and as a consequence, increases in signal gain were realizable.

The well known ray geometry properties of ultrasound posed a particular problem but were eventually resolved through the development of a multi frequency, multi element, rotating parabolic array which covers all possible angles of incidence of sonar signal and thereby guarantees against signal loss. Hence, the objective of very low cost, highly robot pseudo-vision sensing was effected.

The next challenge was the manipulation and interpretation of the massive quantity of real time data generated. Here, a radical departure from map based techniques was utilized. Rather than creating global "maps" of the desired domain the data is preprocessed in real time to yield a highly condensed "symbolic navigational table"

The Expert System Module contains the generalized task definition. For example, the "meaning" of "cleaning" in a global sense. This definition is then integrated with the Global Symbolic Data which contains salient domain geometry information gathered in real-time as well as "inferred" on the basis of past data, and fed to the Navigator Module which formulates navigational ideas to best effect the desired task in the given domain. Note that this Autonomous Navigation Control System does not rely on historical or a priori domain specific data of any kind.

Also noteworthy may be the fact that the path planning modules embody elements of fuzzy logic knowledge approximation and reactive local task planning schemes.

Given a generalized application, the vehicle being developed at Cyberworks laboratories begins to execute the application without foreknowledge of the domain size, complexity, geometry or the nature of objects within the domain.

Utilizing short-range sensors, local data are gathered in real-time. Data compressions and "filtering" are executed in real-time to decompose the local data into a series of vectors and symbols such that the character of the local domain is retained without the retention of the original vast set of Cartesian points. The set of symbolic local data are consolidated into a signal global descriptor which is dynamically optimized into a further reduced set of vectors and symbols encompassing not only the original object placement data but additionally, navigational-assistance data for navigational path planning through the domain.

As the environment is scanned, the data is software pre-processed and salient data is stored in RAM. New salient data is then analyzed in order to reorganize and possibly discard portions of past salient data. Inferences are then made based on this process of data reorganization. The inferences are further verified or modified based on new salient data collected. This process operates in real-time and is the basis upon which the guidance system steers the robot. What data is considered salient and what is not is determined by a lengthy topological rule hierarchy expert system which act as a form of data filter.

Movement error correction is achieved in two ways. First, the robot receives a once-only calibration for the slippage characteristics of each ground surface on which it is to operate. Hence, slippage errors are largely predictable. Additional errors are present in the form of inaccurate ranging data from transducers. This problem is rectified through the use of "mathematical error-vectors" associated with each bit of ranging data. These error-vectors, once analyzed, present an accurate picture of object location and nature. "Approach vectors" guide the robot along the path at least probable error to the desired location. Key landmarks and a pseudo-wall following algorithm are also used to reorient the vehicle.

To improve computation efficiencies, Cyberworks is experimenting with new types of data set representations. In general, rather than storing hundreds of thousands of bytes of Cartesian map data, data is reduced in real-time to navigational descriptors which define the nature of free space in the domain through which the robot travels. This results in a reduction of stored and manipulated map data by two to three orders of magnitude. A correspondingly large reduction in data manipulation and interpretation time results. Thereby, real-time computing is achieved without a priori data.

General slippage, non-ideal angular visual resolution, random noise errors and other non-idealities corrupt map data. Cyberworks' approach is to associate probable error "vectors" with highly critical data sets. These vectors combine to reduce or normalize the degree of error in the system and to cancel its effects to some degree. In addition, a new PC based camera vision slippage control system has been developed for low cost realtime application.

Dynamic elements in the domain are dealt with by dividing the observable space into regions which are time multiplexed. Comparisons can then be made to filter dynamic from static elements. This approach has had limited success but is significant in its ability to ignore various types of transient dynamic events such as moving people and, to some extent, even noise.

A new extremely rich "Operating system" and "Utilities Tool Box" set was also developed which provides a very high level of navigation and sensory data abstraction while simultaneously providing an abundance of "hooks" to "tickle" low level system parameters. Several hundred such operating system functions and utilities are embedded into the system to simplify third party applications development and system portability for alternate embedded applications. This will permit the very rapid development of new high level applications by university researchers and OEM's using the basic building blocks, subsystems, software, sensors and development tools already developed by Cyberworks.

Long Term Test Results

The above architecture has been implemented on three diverse types of platforms for real world evaluation. The first is a fully autonomous vacuum cleaning robot. "CyberVac" is a robotic vacuum cleaner with self-navigational capabilities so advanced that it can be placed in a complex room and navigate around furniture in such a way that the entire floor surface of the room is methodically and efficiently cleaned without preprogramming and without an inefficient "first pass" to "learn" the room. If the objects in the room are reorganized, or moved unexpectedly, CyberVac efficiently and intelligently covers the new floor surfaces without the inconvenience and expense of reprogramming. This demonstrates CyberVac's ability to "understand" and intelligently service a complex area without programming or human assistance.

Cyberworks developed a novel methodology for the navigation path planning of its series of cleaning robots. The approach to surface coverage is of a "non-deterministic" nature. This means that the robot may take differing yet equally (roughly) optimal routes on various occasions each time it is to cover a given domain even if that domain remains unchanged. The need for such a dramatically unorthodox approach arose from the realization that due to sensor data non-idealities, uncertainties associated with slippage, and imprecise origin locations and orientations, the world view of a static environment can seem different each time a robot executes its task. Since an infinite number of geometric configurations can occur due to various combinations of obstacle placement in various sizes and shapes of rooms and buildings, and given that such combinations are further mutated by the forementioned non-idealities, it is mathematically infeasible to guarantee 100% perfect coverage for every possible configuration. However, the chosen methodology does have the advantages of eliminating the need for human input and performing the surface coverage task with a generally increased level of optimality and completeness than its human-driven counterpart. In this sense, the term "human scale performance" comes to mean (a) the execution of complex tasks with little more apriori input than normally required by a human, (b) the execution of a complex task with equal degrees of efficiency as human performance, and (c) the execution of a complex task with "tolerable imprecision" akin to the realistic levels of non-mission-critical imprecision exhibited by human counterparts.

The second platform to which the system has been ported is a multifunction sentry type robot. Three such robots were sold in 1992 to a major Japanese machine tools manufacturer for factory inspection tasks. This implementation dubbed "CyberGuard" was used to monitor factory operations by a factory manager from a remote location such as another office. In this way the manager could converse with staff, trouble shoot defective equipment, etc. without the need to actually be on-site. This is a multifunction robot which combines the capabilities of CyberVac with security, surveillance and other miscellaneous tasks to act as a kind of "surrogate body" for a human being. The CyberGuard Robot is designed to randomly and autonomously patrol a building and when directed, go to specific locations in the building automatically without the aid of embedded lines in the floor. The robot can be outfitted with a variety of sensors or gauges which transmit data (video, sound, information, etc.) to a remote central monitoring station. Several robots can be used in one building to be monitored by a single security guard in a secure location. This design can also easily be adapted for AGV applications in factory automation.

The third implementation dubbed "CyberScooter" was developed for a major manufacturer of wheelchairs. A sonar vision array mounted to the front of the scooter automatically senses its surroundings and limits the maximum speed of the scooter depending on the proximity of people or objects in its path. This feature is especially of benefit to children and people with poor fine motor coordination abilities. CyberScooter demonstrates the ability of the core technology to be used in a wide range of vehicle safety systems.

The above systems have proven highly robust in real world settings. In the case of CyberVac for example, Cyberworks' engineers were surprised to learn that four machines sold to a contract cleaner in Atlanta were being operated daily by a cleaning employee who could not read or write (information verified by on-site visits) thus attesting to the autonomy of the CyberVac's system architecture.

Future Directions

Cyberworks is currently developing new fuzzy logic navigation algorithms, pattern analysis machine vision systems, inertial guidance mechanisms and laser rangefinder imaging systems to expand the range of applications for the core architecture.

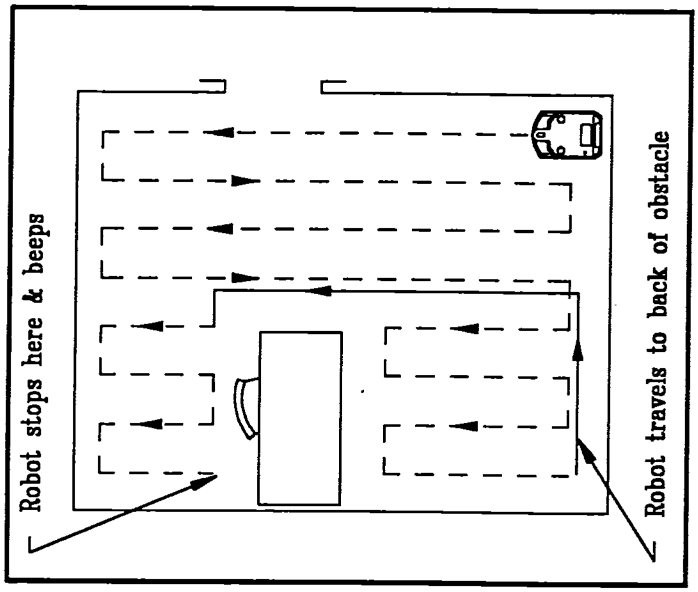
In an effort to increase the robustness, richness and portability of the navigation system, Cyberworks will increase its collaborations with universities and research groups worldwide (Cyberworks currently cooperates with several universities and institutes in Germany, Singapore and Canada). Simultaneously it will accelerate the rate at which it works with universities and OEM's to port its navigation system to other platforms such as mining trucks, AGVs, and consumer devices.

Summary

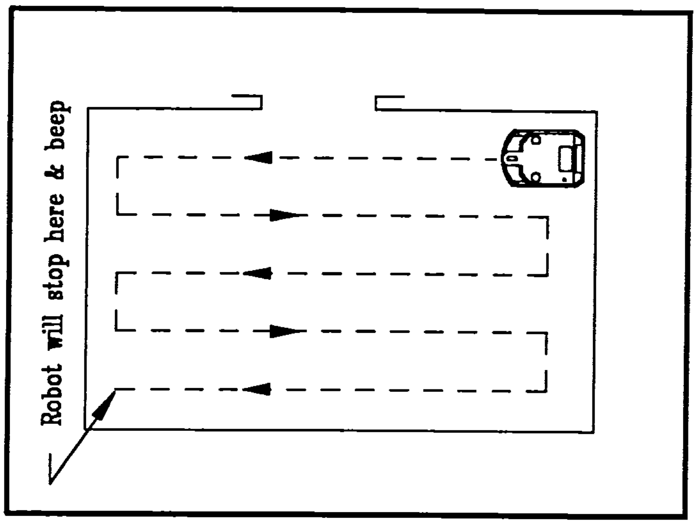
Our research stresses the realization of new concepts which will lead to greater levels of autonomy and lower systems costs. The concepts presented involve primarily the development of novel sensory input systems and data processing methodologies. These systems have been implemented and tested on several platforms and are being applied to the real-time execution of various tasks such as cleaning buildings, building sentry and material transfer. As well, the experimental platform itself is being offered for third party research. The ultimate aim of the research is to reach human scale performance levels for certain specific applications while maintaining realistic price/performance ratios.

Acknowledgements

To the staff & supporters of Cyberworks for making this technology and this paper possible.



Room with Obstacles



Robot's path in a room with no obstacles

FIGURE 6

TYPICAL CYBERVAC NAVIGATION PATTERNS

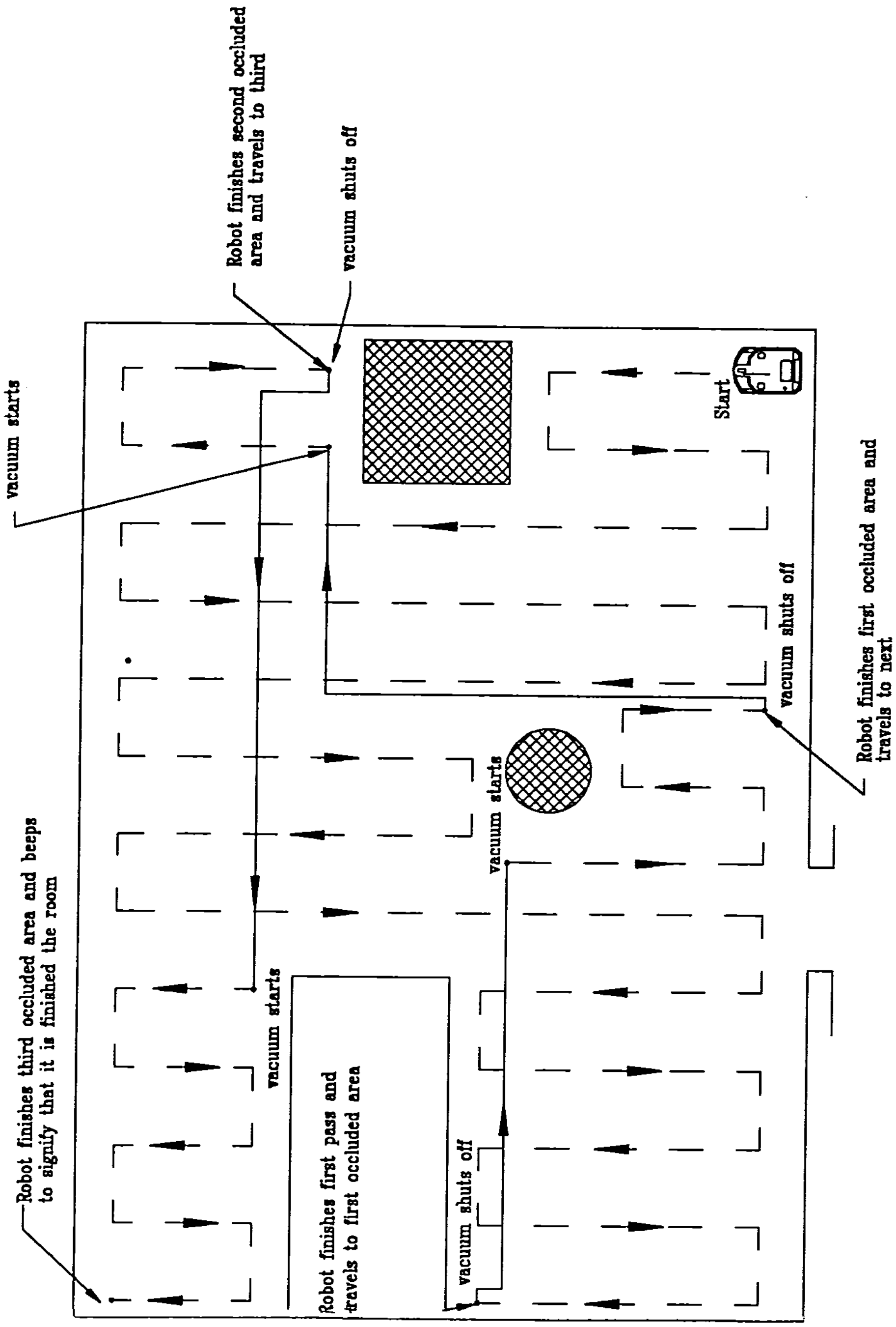
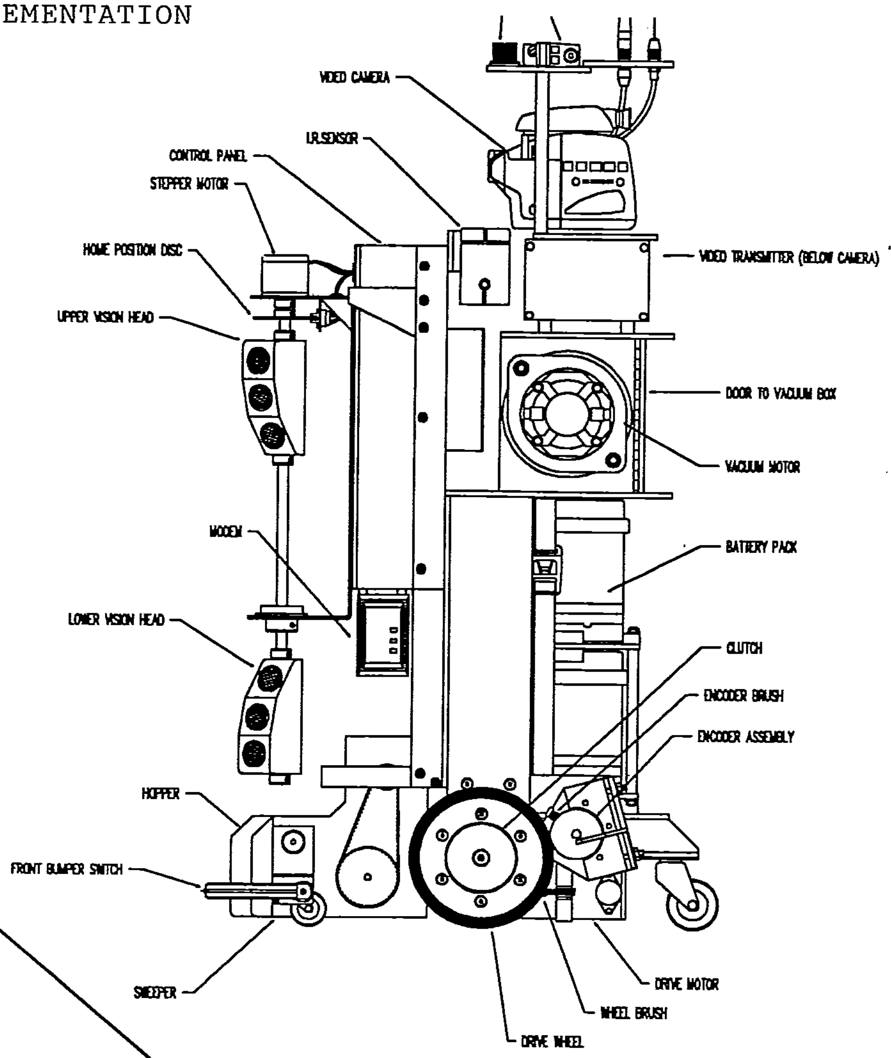


FIGURE 7

TYPICAL CYBERVAC NAVIGATION PATTERNS

FIGURE 8
Side View



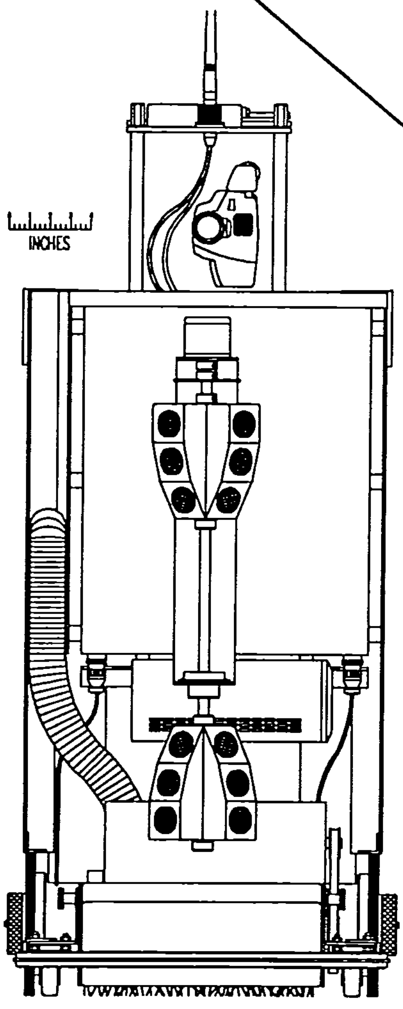


FIGURE 9
Front View