Practical Requirements for a Domestic Vacuum-Cleaning Robot

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Abstract

Consideration of the environmental, commercial and legal constraints on a practical home vacuum-cleaning robot suggests that the best configuration is a compact single-purpose vehicle designed to map and follow a deliberate path. This configuration, suitably equipped with the necessary external and internal sensors, serves to define the AI requirements for mapping, path following, contingency handling and user interface.

Introduction

Developing a commercially-viable robot for autonomously vacuuming a domestic household poses requirements qualitatively different than those encountered in a research or industrial environment.

As diagrammed in Figure 1, environmental and commercial/legal considerations define both the viable configuration options and the sensor requirements. All of these then combine to drive the required AI capabilities. Over the long term, it can be expected that some infrastructure changes will be made to accommodate robots, but the initial products must deal with the world as it is today.

The purpose herein is not necessarily to advocate specific AI methods or representations, but rather to describe the overall practical considerations and the AI requirements that are ultimately derived. It will be assumed that the robot must use existing or near-term mechanical and electronic technology.

Environmental Considerations

The constraints imposed by a house (or apartment) by itself are fairly obvious. Rooms are located and configured randomly, and are connected by various types of doors. Certain doorways or other openings will lead outside or into closets. Open stairwells and fireplaces may be unprotected. Floor texture and hardness can vary greatly. Obstacles can be uniquely configured, dynamically located, fragile and possibly expensive. And, of course, lighting conditions can range from complete darkness to direct sunlight.

One consideration results directly from the vacuum cleaning task. Low-profile obstacles such as extension cords, throw rugs and newspapers may not block the robot's path, but could jam the vacuuming system.

The presence of humans and their pets makes things more interesting. "Guest" adults may be unfamiliar with the robot. Children will attempt to ride upon, mislead or otherwise play with the robot. Infants will be inattentive and especially vulnerable. Pets may attack the robot, or perhaps just block its path. TVs, stereos and children will generate a high ambient noise level. Unfortunately, it must also be expected that objects will be dropped on, and liquids will be spilled upon the robot.

Commercial and Legal Considerations

Beyond the household itself, several other issues will determine the robot's practicality as a consumer appliance.

First, it must be assumed that the robot's owner will neither have nor desire any understanding of robotics, electronics or AI. It should also be expected that any "Owner's Manual" will *not* be read. Ideally, the owner would be able to install the robot using a set of simple instructions. An acceptable alternative would be to have the robot initially installed by a trained technician, who would then provide the owner with simple instructions for use. Optimally, no physical changes to the household should be required, but the placing of small passive markers at selected locations would probably be acceptable. In any case, installation should normally require less than one hour.

Second, the robot must be extremely reliable and robust in operation. Other than occasional replacement of the dust bag, the robot should not require maintenance more than once or twice a year. It must be unaffected by (or compensate for) high ambient noise, radio transmissions, unshielded computers, infrared remote controllers, and magnetic fields. It must recognize any internal failures and continue to function as normally as possible. Also, it should have an effective mechanism to reduce the chance of theft or other unauthorized use.

Third, the existing legal climate requires that the robot be extremely safe in operation. Any active sensors must not emit light, microwaves, magnetic fields, heat or sound at a level that could damage humans, animals or objects, even at very close range. The robot should not cause interference with TVs, radios or radio-telephones. To minimize legal liability exposure, the manufacturer will need to document and demonstrate through exhaustive testing that the robot's mechanical, electronic and software systems have been designed and built to safely handle *every* possible operating contingency.

Naturally, the robot should perform its vacuuming task at least as effectively as an average human. Speed of vacuuming is not likely to be critical, but thoroughness will be. Coverage of corners, edges and "nooks and crannies" will be especially important.

Finally, notwithstanding all of the above, the robot's development, manufacturing and warranty costs must be kept to a minimum. Though it is not clear how much people would be willing to pay for the convenience (and prestige) of a robot vacuum cleaner, most high-end consumer appliances sell for less than U.S. $3000. In addition, the robot will have to offer equal or better price/performance than other competing automatic vacuuming products.

Proposed Configuration

Many possible robotic system configurations are possible, ranging from colonies of vacu-roaches to a fully anthropomorphic robomaid. The approach advocated here is for a single compact wheeled robot specifically designed for household vacuuming. It is submitted that this configuration offers the best compromise between cost, practicality, and consumer acceptance. A sketch of a possible implementation is shown in Figure 2.

The robot would be capable of operating completely autonomously, with all power and computation on-board. To maneuver under tables and into confined spaces, the robot should be as compact as possible, though vacuum system requirements and existing battery technology would limit the minimum size and weight. It would have a single charging-dock "home base" that could also be used as a diagnostic platform by a technician. Limited control of the robot would be available through a handheld device similar to a TV remote controller. Robot-to-human communication would be done using speech generation and simple indicator lights.

For reasons of cost and complexity, no stair climbing capability is proposed. If the household contains step-ups or split-level stairs, ramps would be need to be installed. Multistory dwellings would require either multiple robots or a specialized transport cart.

Normal operation of the robot would, superficially, be simple. When first installed, the robot would automatically explore its surroundings to generate an internal world model, which would then be used to plan vacuuming paths. Subsequently, either on a regular schedule or when specifically commanded by the owner, the robot would perform its vacuuming chores. Vacuuming would be accomplished in one pass if possible, but a multiple pass approach would be acceptable.

Sensor Requirements

The choice of sensors will drive both the hardware and software requirements, and will have the most effect on the overall production cost of the robot. It is argued that the best way to guarantee coverage, reliability and safety for the lowest overall cost is to use many redundant, low-cost sensors.

Some sensors would be used for mapping, position estimation, obstacle avoidance and collision detection. Likely candidates would be the usual: ultrasonic sonar, passive light detection, reflective IR, pyro-IR, wheel odometers, and a compass system. If navigation markers are used, they may require a specialized sensor. Most important, though, would be a comprehensive bumper system capable of detecting the direction and location of *any* contact with the exterior of the robot.

Other sensors would be necessary to cope with operational contingencies. These would include drop-off detectors, inclinometers, moisture indicators, a lift detector, a vacuum inlet microphone, an external temperature sensor, a remote-control receiver, and a charging-dock homing device. Any external openings would require intrusion detectors.

Self-monitoring would necessitate internal state sensors such as motor ammeters, battery charge indicators, a dust bag fullness sensor, an internal smoke/ozone detector, and temperature sensors for the motors, electronics and batteries. Special sensors would be needed to detect unauthorized tampering or disassembly.

Passive vision and laser range-finders are, at the present time, too expensive for consideration. A structured-light sensing system *may* be cost-effective if the light intensity could be kept at a safe level. External microphones could be used to detect large or unexpected changes in the ambient noise level, but the vacuum-system and environmental noise would probably preclude their use for speech recognition, or even speaker identification.

Last, but not least, many of the sensors will need to be self-calibrating and/or self-testing and/or fail-safe. If any sensor has failed, or is operating outside its expected limits, the robot's processor should be aware of the situation. The robot should be able to operate (or shut down) safely with one or more of its sensors inoperative.

AI Requirements

Based upon the foregoing configuration and operational assumptions, the robot's AI software and hardware must be able to: 1) Create and maintain an internal model of its household; 2) Plan and execute an efficient vacuuming path; 3) Respond to operational contingencies and, 4) Diplomatically interface with its owner.

Since the robot will be spending most of its life in the charging-dock, it will have a considerable amount of time to reason about its environment and plan its operations. Thus the AI methods for modeling and planning can be selected for completeness rather than time-efficiency. However, contingency handling and user-interface will usually require real-time response.

Exploration and Mapping

Likely, the most intellectually challenging AI development problem will be getting the robot to autonomously build and maintain a useful model of its environment.

During the initial exploration phase, the robot will have to perform real-time fusion and interpretation (or logging) of the often ambiguous and contradictory data from its many external sensors. It will need to determine where it is, where it has been and where it still needs to explore. Immediate creation of a "map" would not strictly be necessary as long as the robot avoids getting lost.

For its modeling, the robot will have to distinguish between vacuumable floor space, forbidden space, and various obstacle types. Forbidden space would include outdoor areas as well as special areas within the household. Obstacle types will range from permanent (walls, stairs) to variable (doors) to static (cabinets) to moveable (chairs) to temporary (toys) to mobile (humans, pets). The situation will be further complicated if the environment has ramps coexisting with steps and stairways.

Finally, the robot will need to constantly update the model to allow for the inevitable changes in the household. Ideally, new sensor data would be acquired and logged during normal vacuuming, though separate exploratory excursions would be acceptable. This data could be integrated into the mapping and planning while the robot is recharging.

Path Planning and Execution

Compared to mapping, planning a vacuuming path is relatively easy: the planner need only ensure that all the vacuumable space is covered. To minimize time and battery usage, the path should be as short as practical, but there is no need to eliminate redundant coverage. The path should have some edge overlap to allow for positioning errors. A more difficult problem is determining how to maneuver the vacuum suction unit into confined areas.

Assuming adequate modeling of the environment, execution of the vacuuming task is, in theory, some variation of navigation and path-following among obstacles. As with the exploration phase, it is important that the robot always be able to find its charging-dock.

Operational Contingencies

Of course, in addition to its "normal" operation, the robot must be able to handle various real-time contingencies. This will probably be the most time-consuming software development problem; the sheer number of possibilities (and combinations) is daunting.

Some contingencies would need a response, but would not be time-critical. They include: owner-commanded return-to-base while vacuuming or exploring; unable to determine location in household; obstacle(s) blocking path; room on vacuuming path is inaccessible; interior door is partly opened; charging-dock not accessible; charging-dock not charging; vacuum dust bag is full; battery charge getting low; sensor temporarily inoperative; sensor failure suspected; known sensor failure; high motor temperature; tampering sensor activated.

Other problems will require an immediate decision and response. A few possibilities are: emergency stop from remote controller; unexpected bumper hit; object intrusion into an external opening; unexpected drop-off indication; tilt angle outside normal limits; moving obstacle approaching rapidly; drive wheel(s) stuck; drive wheel(s) off the ground; moisture sensor activated; object trapped in vacuum inlet; sudden change in the ambient noise, light or temperature level.

Clearly, there are many, many other possibilities. Consider also that multiple problems might occur simultaneously, and that new problems could appear while the robot is trying to manage previous ones. In some cases, simply stopping the robot is not enough -- indeed, that may be the *worst* action to take. Deliberate, intelligent response is required.

Operator Interface

Perhaps the most interesting area of AI development will involve facilitating the robot's relations with its human masters.

Since it is assumed that the robot's owners will be technically naive, poorly trained and possibly malevolent, the robot will have to do more than simply follow commands entered into the remote controller. Based on the context of its situation, the robot will need to intelligently *interpret* commands and act appropriately. If necessary, it could use speech generation or other means to provide assistance to the owner. However, it should *never* respond to commands or request help in a way that would confuse, aggravate or frustrate a well-intentioned human. Nonetheless, the robot must not permit itself to be operated in a manner that could damage it either externally or internally, and it should not allow itself to be guided (or goaded) into any forbidden area.

Through it all, the robot-human interface will have to give new meaning to the phrase "user-friendly".

Conclusion

All things considered, what might be thought of as a simple task in a relatively benign domain is in fact quite demanding of robotic and AI technology. Obviously, choosing a different system configuration than described above could result in differing AI requirements. But whatever approach is used, the practical and commercial requirements of the real world will remain.

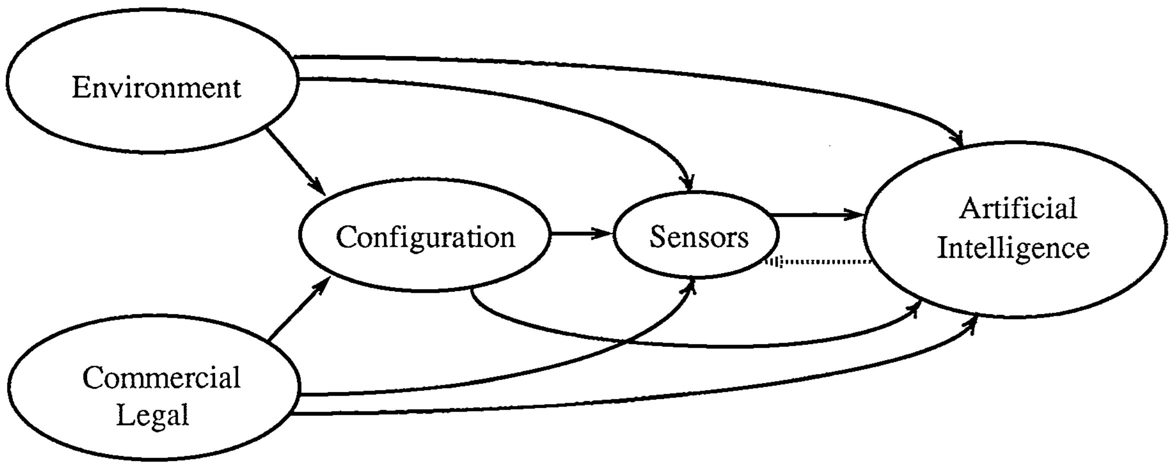

Figure 1

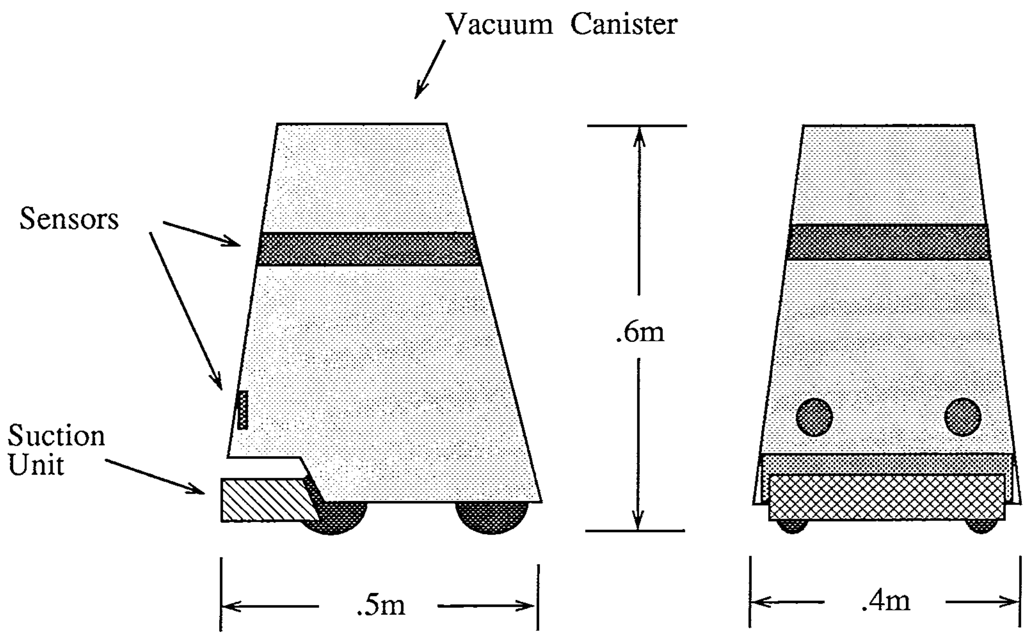

Figure 2