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Mobile Robots — a Short Overview

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Mobilni roboti — kratek pregled

Članek podaja pregled raziskav in razvoja mobilnih robotov. V uvodu podajamo zgodovinski razvoj mobilnih robotov. V nadaljevanju so ločeno predstavljeni mehanizmi za gibanje in inteligentni deli mobilnih robotov. Gibalni mehanizem mobilnega robota so lahko kolesa, gosenice ali noge. Senzorji, računalniki in programska oprema sestavljajo inteligentni del sistema. Z njihovo pomočjo mobilni robot zaznava okolico, načrtuje svoje gibanje in krmili izvajanje nalog. Na koncu navajamo probleme, ki jih še bo potrebno rešiti, da bi bili mobilni roboti okretnejši in s tem zmogljivejši.

In this paper we present an overview of the present status of mobile robots research. In the introduction we give a brief history of mobile robot development. Then two main components of mobile robots are discussed; mechanical component for movement and intelligent for sensing and planning. A mobile robot can be wheeled, legged or of a crawler type. The intelligent part consists of sensors, hardware and software to perform perception, planning and control. Despite great expectations and large invested efforts, today's mobile robots have a lot of deficiencies. Some problems of making mobile robots more flexible and efficient are discussed at the end.

1 Introduction

Research in building machines which could replace man at hazardous, strenuous and repetitive tasks began in the early sixties. At the time, the focus of the research work was on design and control of fast, accurate and easy to program robot manipulators. A few years later, a project was started at the Stanford Research Institute with the main idea "to study processes for real time control of a robot system that interacts with a complex environment". The result of these efforts were that two versions of SHAKEY, an autonomous mobile machine, were built in 1968 and 1971 [18].

Encouraged with these first results, the research efforts in robotics throughout the last two decades concentrated on two main directions. The first direction was to design a dexterous and versatile robot manipulator which could be used for various tasks in manufacturing and for manipulation of objects. The second direction was to build a mobile robot that could be employed in hazardous environment such as for example in prevention and fighting against fires, as well as in underwater and space exploration.

The problems encountered in the design of mobile robots greatly differ from the problems in robot manipulator design. The design of a mobile robot includes

- development of a mobile mechanism and its control technologies and
- development of intelligent techniques for performing a variety of tasks under partially predictable or unpredictable conditions.

Research on mobile robots, which had started in the late sixties, continued in the seventies with the work on the "Stanford Cart" project [16]. The project was supported by DARPA, NSF and NASA. The Stanford Cart, a wheel-driven mobile robot, was a testbed for indoor and outdoor navigation in an unknown environment. Capable of short runs only (1 meter every 10–15 minutes), the Stanford Cart was not a success. Another project running at the same time was the "Mars rover" project at JPL [4], sponsored by NASA. The lack of efficient on-board instrumentation (computers and sensors) limited the ability of these robots and caused the Mars rover research program to be stopped. The project was revived in the beginning of eighties with the growing interest in planetary exploration.

The first great success in mobile robots was HILLARE, developed at LAAS, France [7]. The robot was capable of perception and self-navigation, which included building a map of unknown space using acoustic and visual sensors, constructing three-dimensional representation with the information from two-dimensional optical vision and a laser range finder, position estimation, path planning and obstacle avoidance.

During the eighties mobile robots attracted increasingly more attention. Two trends of research can be distinguished. A lot of laboratories in USA, Europe and Japan followed the system architecture of HILLARE and developed their own vehicular mobile robots ([16], [17], [21], [23], [5]). Some of these robots are already used for material handling in industry [10]. The second and quite different trend of

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research is concerned with the design of multilegged robots and the study of their kinematics and dynamics ([1], [2], [20], [19]).

Despite these efforts, hardly any existing autonomous machine today can carry out a mission as difficult as inspection and repairing of underwater structures, maintaining nuclear plants or assembling and servicing in outer space. The following sections discuss what should be done in order to attain such a flexible, dexterous and intelligent robot system.

2 Inside a mobile robot

A mobile robot is a robot capable of intelligent motion and action without requiring constant human supervision (teleoperator control) [4]. Such a robot would be applicable in situations where man's presence is unsafe, impractical and undesirable. To achieve this objectives a mobile robot should be able to:

- complete a prespecified mission in a structured or partially structured environment,
- cope with uncertainties in the working environment,
- reason and resolve unknown situations,
- exercise self-diagnosis and self-recovery, and
- communicate with the human operator.

The main components of a mobile robot are its mechanical parts for movement and its sensors and intelligence (Figure 1).

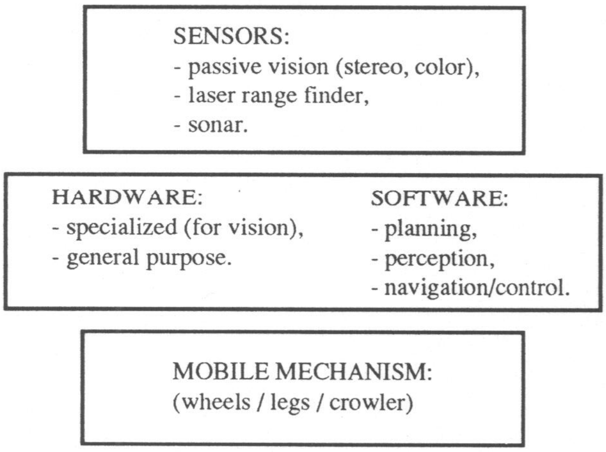

Figure 1. Main components of a mobile robot.

2.1 *The mobile mechanism*

The mobile mechanism is the mechanical part of a mobile robot. With regard to its mobile mechanisms, a mobile robot can be classified as wheel-driven, legged or crawler-type.

Most of the smaller mobile robots, designed to operate mostly indoors or in relatively controlled outdoor environments, are *wheel-driven*. These robots are usually less expensive and provide a testbed for research in perception, navigation, guidance, planning, obstacle avoidance and goal recognition. This category includes the LAAS robot HILLARE [7], CMU NavLab's robots [21], CMU MRL's robots [16][17], CESAR's HERMIES-III [23], the SRI's MARS [12], INPG's Surveillance Robot [5] and VaMoRs [6].

The *crawler-type* mobile mechanism is suitable for work in rough terrains. This mechanism could be used for off-road driving (in military applications and planetary surface exploration) as well as in some complex indoor environments (climbing a staircase). A representative of these rather bulky machines is FMC Corporation's mobile robot [15].

The *legged mechanism*, due to the complex multi-joint structure, is the most nimble mobile mechanism. This mechanism is expected to be common in particular types of future robots. Applications of legged robots range from underwater investigation (AQUAROBOT [1]), through off-road work (suspense vehicle [3]), to planetary exploration (Ambler [2]). To attain agility in such a system many problems have to be solved. These include: reducing the weight of the mechanism; optimal distribution of the mechanism's elements; statical and dynamical stability; choice of gaits which permit walking under predetermined conditions (walking on staircase and slope, striding over obstructions, etc.); selection of appropriate actuation and control of multi-joint mechanism. Other representatives of this walking machines are the biped robot WR-12 [20] and Raibert's one and two legged running robots [19].

2.2 *The intelligence of a mobile robot*

The intelligent part of a mobile robot consists of sensors, computer hardware and software. Each of these components plays a particular role in robot's intelligent behavior.

Sensors

A common characteristic of all mobile robots is their ability to navigate within the environment. In order to achieve this, the robot must be capable of sensory interpretation (ability to determine its relationship to the environment by sensing) and reasoning (ability to decide what actions are required to achieve its goals in a given environment) [14]. The ability of the robot to "see" the environment with a set of different sensors is called perception.The type and number of sensors included in a mobile robot's sensory system are determined mainly by the complexity of the mission, the uncertainties in the working environment and the level of autonomy of the robot.

The perception ability of a mobile robot in industry, focused on reaching a designated location in space, is modest. The only thing the robot should be aware of is its position relative to the goal. Therefore, these robots are equipped with position-determination systems based on dead reckoning (encoders mounted on the wheels [4]) or inertial navigation techniques (gyros). The vast majority of mobile robots in industry constantly communicate with the center (master computer). Thus the techniques for sensor interpretation and reasoning, which are very important for intelligent behavior, do not have to be very sophisticated.

When the robot is designed for work in a complex indoor or outdoor environment, where local constraints obstruct the robot's free motion toward the goal, the robot is additionally equipped with obstacle-detection sensors in the form of sonar arrays or stereovision. A more accurate positioning perception system includes either a laser or infrared based beacon system or a vision system for landmark recognition. Many existing robots employ multiple sensors to increase the accuracy of the gathered information and/or to complete the world model by fusing the sensors' output. For example, CMU's NAVLAB [21], which is capable of road following uses a laser range finder to provide three-dimensional information about the scene and a color camera to provide image information such as color and texture. VaMoRs [6] uses two black and white cameras for road following (wide angle lens) and obstacles avoidance (tele photo lens). Uranus [17] uses stereovision and a sonar array for building an occupancy grid. There are cases when the sensory system grows large. For instance, the FMC Corporation's mobile robot [15], capable of object and landmark recognition, real-time road following, obstacle avoidance and walking on slopes includes: seven color cameras, an inertial navigation system, a dynamic pitch/roll sensor, a forward-looking infrared sensor, and a sonic-imaging sensor. The robot determines the type of the terrain by combining color, texture and shape.

The less structured the environment is, the greater is the necessity of sensing and reasoning and consequently, more powerful on-board computational resources are required. Outdoor navigation is, thus, much more demanding than indoor navigation. Nature dynamically changes its form, so the active perception (constantly updating of the world model) is necessary. Dickmanns [6] proposes an integrated spatiotemporal approach for modeling the surrounding world in space and time (4D model). Sensor data fusion (combining, merging the information from different sensors) and active perception reduce sensor errors, maximize the sensor use and increase robot capabilities. However, they generate problems, the solutions of which require particular software and hardware capabilities. Problems connected with the sensing process include modelling of sensor performances, choosing data fusion strategies and choosing a appropriate data representation[8].

Computer Hardware

Computing architectures for mobile robots evolved with the development of the microprocessors. Early vehicle experiments relied on remote mainframe computing capabilities, linked to the vehicle through a cable or a radio-frequency telemetry link [16]. As a result, the autonomy of the vehicle was minimal. The rapid development of microelectronics has made it possible for these limitations to be overcome. Most of today's mobile robots, except for robots demanding specific locomotion mechanisms (for example Raibert's robots [19]), carry their computational load on-board and are completely independent of remote computing facilities.

An on-board multiprocessor computing resource combines specialized hardware with general purpose hardware. Specialized hardware is normally required for high speed numerical computing, which is in turn needed for low-level vision (filtering, feature extraction and data fusion). At the same time a general purpose computer architecture is needed for symbolic processing in the planner and partially in the perceptor. These two types of architecture must be efficiently interfaced in order to facilitate the transformation of numeric data into symbolic representations.

Up to now, on-board multiprocessor computing has taken several forms. The simplest organization of hardware resources is a master-slave architecture (Stanford Cart [16]). This organization is often used in industry and teleoperation (AQUAROBOT [1] and ATTV [9]). In more complex systems the planning, navigation and pilot modules can be organized as a star hierarchies or as tree hierarchies (HILLARE [7] and JPL Rover [4]). The physical components of the system are interconnected through a local area network in a bus communication configuration (Intel Multibus I/II, Ethernet), forming a loosely coupled system. Processes communicate with message passing. In the more tightly coupled systems modules are organized as cooperating experts, communicating through a blackboard. A blackboard system consists of a central database (LM-local map), a process (LMB-local map builder) that manages this database and LMB interface for synchronization and data transfer between system modules (NAVLAB [21]).

While some mobile robots use Intel's [6] or Motorola's microprocessors for general purpose processing, others for the same purpose incorporate several SUN and VAX minicomputers on-board (NAVLAB [21]). The sensor data processing is almost everywhere done on specialized hardware. For example, the sensor data processing in HERMIES III [23] is accomplished by its NCUBE parallel processing supercomputer. Dickmanns [6] developed a multiprocessor vision system BVV2 for real time scene analysis and interpretation.

Computer Software

The main components of the intelligent behavior of a mobile robot include planning, perception and navigation/control.

The *planning system* activates the perception system to build local environment maps. With the knowledge about missions, the sensor information about terrain and the capabilities of the autonomous system this module plans a sequence of actions and routes that lead to the goal accomplishment (real-time path planning and planning of the robot arm motions during assembly or maintenance operations). The planner directs the control/pilot module to perform the planned actions and orders the perceptor to monitor the execution of the task. Depending on the level of autonomy the mobile robot exhibits or does not exhibit intelligent behavior as reasoning, high level decision making, diagnosis and learning.

The *perception system* interprets sensory data. The key problem in sensor interpretation is to establish a mapping between the signal output, which depends on the used sensor, and the properties of the 3D world. The problem becomes more complex when data fusion strategies are applied for modelling of the world. Most perception systems are knowledge based, that is they incorporate knowledge about the scene. The use of scene knowledge improves the reliability of the interpretation. However, the usage of the system is then limited to that prespecified scene. But, even if we give the robot exact information about its environment, the problem of sensor data processing remains difficult (for example, the problem of feature extraction). The intentions of the perceptor system designers are to make the perceptor module domain-independent, modular and extensible. To gather useful information for other modules of the robot system the perceptor in addition to data processing performs data interpretation. The module determines the shape of the observed objects (geometrical reasoning) and the position and relationships between objects on the scene (spatial reasoning). For the needs of other system modules, models of the world are organized in hierarchies (geometrical, topological and semantic).

The *navigation and control module* uses fused local maps and the mobile mechanism's characteristics to plan a local path and to determine the corresponding mobility commands.

In the mentioned software architecture, each subsystem is as skillful and independent as possible and communication between subsystems occurs at as high a level as possible. Most robot systems are distributed multisensor systems, which components and processes communicate in a way described in paragraph 2.2. In order to support real-time applications by coordinating the modules' activities and interprocess communication an appropriate operating system is needed [13].

3 Perspectives

Robots have often proved themselves as fast, accurate and easy to program machines in various well-structured industrial environments. Human operators have applied robots in teleoperation applications such as underwater exploration (AQUAROBOT [1] and ATTV [9]), and digging holes and onground construction [24]. Automated guided vehicles have found applications in many factories in USA, Europe and Japan [10].

Encouraged with this results a great amount of scientific efforts has been invested in increasing the robots' autonomy by making them mobile and "intelligent". However, if we consider the presence of mobile robots in everyday life the results are far from satisfactory. Most mobile robots are still "dumb and clumsy" [22], slow and inflexible, and therefore, not prepared to take over situations that require anthropomorphic capabilities. State-of-the-art hardware and software technologies, which have been successfully examined in the laboratory environment are not easily transferable to everyday applications. An inevitable intermediate step to fully autonomous machines is telerobotics (telepresence), where a human operator acts merely as a supervisor, intermittently communicating to the mobile robot information about goals, constraints, plans, suggestions, assumptions and getting feedback information about problems, accomplishments and if requested, raw sensory data [11]. It is more likely that existing mobile robots will be used in some telerobotics operations than as completely autonomous machines. Some of the promising applications of telerobotics are: deep-see mining and salvage operations, servicing/assembly tasks in space, and maintenance activities in nuclear plans and toxic environments ([11], [24]).

Developing autonomous mobile robots, with the properties listed in paragraph 2, will require a technological outreach in both the mechanical and the intelligent part. The more crucial part of a complex robot system is its intelligent part consisting of the sensory and software system. The hardware and the mechanical part stay passive until they are activated by the intelligent part.

Practically every living organism bases its actions on the perceived state of the environment [8]. In comparison with the human being, whose intelligence can be explained as ability "to use information to modify action", the "intelligence" of a robot system is connected with its sensing, reasoning and communicating capabilities. The challenging aspects in creating the intelligent part of a mobile robots are:

- task planning and coping with a dynamical environment,
- scheduling operations and resources (capability of assessing a situation, analyzing the current information requirements of a task, evaluation of device implementation alternatives under uncertainties and computational limitations),
- intelligent information gathering (sensor observation planning by evaluating the sensor system capabilities and sensor fusion strategies [8]),
- diagnosing of malfunctions, replanning and error recovery,
- learning, and
- communication with human operators (speech recognition) and other machines.

Turban [22] states that programming the most of the mentioned processes in the form of expert systems would provide convenient and powerful method of controlling the robot's behavior.

The performances (the maneuverability and the flexibility) of a robot mobile mechanism can be improved with the use of:

- hybrid locomotion systems (legs and wheels, legs and caterpillars, etc),
- modular robot mechanisms (easily reconfigurable, particular elements are useful in particular situations) and
- new materials for robot's body construction and control.

As the field of mobile robots emerges as a separate research discipline, the listed challenging aspects in mobile robot design are a driving force for research work in disciplines such as: control engineering, artificial intelligence, sensor information processing (computer vision), mechanics, chemistry, etc.

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