Environment infrastructure and multi-sensor integration for autonomous service robotics

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Abstract**—**This paper presents an approach to enable autonomous service robots activities based on creation of an infrastructure parallel to the infrastructure of environment for daily human life and on cooperation of robot sensors. A mobile robot equipped with a manipulator is regarded as a service robot. A specific problem of control by the manipulator movement is concerned with changeable position of its base with regard to the position of the environment objects. The infrastructure contains both material and informative components. Material components are adjusted to the capabilities of the manipulator. Robot sensors provide functions based on position information. Control by the robot action starts with the assumption of exact knowledge of the initial pose of a mobile platform with regard to world coordinate system. The odometry sensors are used as metric reference. Visual sensors and laser rangefinder are used for verification of robot's current pose. Proposed collaborative sensors data processing is used to cut down analyzed space of scene by directed selection of the area of interest and to replace the pattern recognition problem solving by the verification of the state of known scene. We proposed the visual informative landmark and mono-camera vision system that provide the robot direct measurement of its 3D spatial position with respect to landmark coordinate system and with additional environment information. It serves as the base to design an environment model representation as a hybrid of topological and metrical maps.

Keywords Collaborative sensors data processing, environment infrastructure, informative visual landmark, service robotics.

I. INTRODUCTION

THE new trends in robotics research out of traditional industrial applications increasingly concentrates on the robots of multifunctional service in unstructured environment and interactions of human being and robot. According to the International Federation of Robotics service robot is a robot that operates semi autonomously or fully autonomously for performing services useful to the well being of humans and equipment, excluding manufacturing operations.

Service robots can be mobile and with manipulation capacity. In dependence on its functions and applications, the service robots are divided in robots of professional service and of personal service.

Professional service robots are used in a variety of applications at work, in public, in hazardous environments, in locations such as deep-sea and space, and in defense, rescue and security applications. They are more expensive than personal robots. According to the International Federation of Robotics analysis, the total value of professional service robots sold up to the end of 2008 was US$11.2 billion with total number of 63,000 units including 20,000 units the service robots in defense, rescue and security applications.

To assist the human and “to live” among people, the personal service robot has to be a multifunctional system and should possess certain level of intelligence. Robots have to be able to communicate with a user and other technical systems including other robots, to process and interpret sensors data, to synthesize the environment model and to monitor the environment state, to plan goal-directed activity, and to realize the plan. It is obvious that these requirements correspond to the general requirements to Intellectual Robotics.

Multi-functional robots will be able to carry out both complex and routine tasks for people in a multitude of environments such as assisting aging populations, aiding people with disabilities, helping in household chores, performing operational activities. Actually service robots for personal and domestic use are mainly in the areas of domestic (household) robots, which include vacuum cleaning and lawn-mowing robots, and entertainment and leisure robots, including toy robots, hobby systems, education and training robots.

The different nature of human beings and technical systems defines a basic difference between them: the universality of the first one and the specialized domain of functioning of the second one. As a universal system the human being needs to solve a variety of problems of different nature. It is problematic to reproduce the universality of human being, but when creating applied autonomous robots predestinated for functioning in a limited problem domain we do not need to design them as universal systems. It is not an artificial restriction: the activity domains differentiation and specialization is widely used by the human being (e. g., workers constructing roads and workers constructing automobiles represents the groups of different specialization).

In designing applied autonomous robots we can follow the general principles of the human functioning and behavior such as the cooperative human being subsystems functioning (sensory-motor functions), cooperative functioning of the human community, creating special infrastructures and information support to simplify a human community functioning, and the activity domains differentiation and specialization. At the same time, it is possible to use the fact that technical systems and human beings can execute some similar actions in a different way. Some times technical systems can perform better than human beings. For example, the autonomous robot can be equipped with a set of sensors that allowed it to perceive signals that can't be perceived by the human beings, can provide the simultaneous omni directional vision, can measure the distance with high accuracy, and for a long time can record exact positions of the objects of its surrounding. The appearance of new technologies including such as creation of the intellectual environment, RFID technology, etc. and the cooperation of the sensors of different nature also is of importance for increase the robot's capabilities (see section 3). We followed this standpoint for the information support of a different degree of generality for the robot autonomous acting - from single sensor subsystems (see section 2) right up to architecture of robot's information-control system (see section 4).

II. Distributed Autonomous Robots Architecture Centralized by Knowledge

An approach, based on the cooperation of various subsystems that provides the robot autonomous functioning, was proposed in [1]. Cooperative functioning of the robot subsystems is defined as the work of all participants to reach the general goal defined by the user and to reach a special common goal that provides or assists successful functioning of each of them. The Distributed Architecture Centralized by Knowledge provides cooperation of all subsystems, such as user-robot dialog supporting, sensor data analysis and world and robot state verification, safe trajectory self planning, and movement control. The main characteristic of the proposed architecture is a bidirectional communication between subsystems in difference of the unidirectional data stream starting with the sensor signals and terminating at motors commands which is exploited by autonomous robot architectures generalized in [2] – [4].

"Centralized by Knowledge" means that the knowledge of the current spatial state of the robot and its environment is defined as a special common goal for all robot subsystems: Each of subsystems sends the corresponding information discovered to the subsystem of the monitoring robot and environment state and has access to the information accumulated by this subsystem to use it for solving its particular problems. "Robot and environment state" is interpreted as the position and orientation of robot and objects of its environment.

"Distributed" means that all subsystems have autonomy and can cooperate with each other in solving their particular problems. All subsystems work in parallel, every one in its specific domain. Every subsystem uses the individual presentation of the model of the environment and the robot model adapted to the process destination. It provides some liberty in the solution of problem of world representation. The information common to all subsystem is: the name of the object model and its spatial state (the position and orientation of the coordinate system of object model with regard to the world model coordinate system. The object name and the object model coordinate system are common for all subsystems.

The knowledge of a current spatial state of the robot and its environment enables us to interpret the model of robot environment as a closed one in the meaning of the material and information flows, which is an indispensable condition of the robot autonomous functioning. It does not mean that robot environment is unchangeable. It means that the possible change can be discovered by the subsystem of sensor data analysis and world and robot state verification.

At the same time, the knowledge of a current spatial state of the robot and its environment can simplify the solution of the particular subsystem tasks. For example, for the subsystem of sensor data interpretation a difficult problem of 3D scene recognition can be reduced to the problem of its expected state verification. In this case it is necessary to define the correspondence of the grasped image of an object to the sample of an object of known class in known position. The problem of pattern recognition appears only in the case of negative answer, but in the same time positive answers for other objects significantly reduce the unspecified space and the number of unknown objects classes of an unspecified part of the image.

The proposed architecture is implemented using as a kernel the mobile robot PowerBot equipped with a set of the sensory systems (ActivMedia Robotics, U.S.A.) [5], predestined to investigations in the field of the Intelligent Robotics (Fig. 1). It is equipped with the arm of 6 degrees of freedom that is the Industrial Robot PowerCube (Amtec GMB, Germany) [6] which has a camera over the gripper.

An enhancement of the PowerBot computational base is fulfilled by creating a local network containing the onboard PC and 4 additional portable computers that allows us to adapt the PowerBot to the Distributed Architecture Centralized by Knowledge [7].

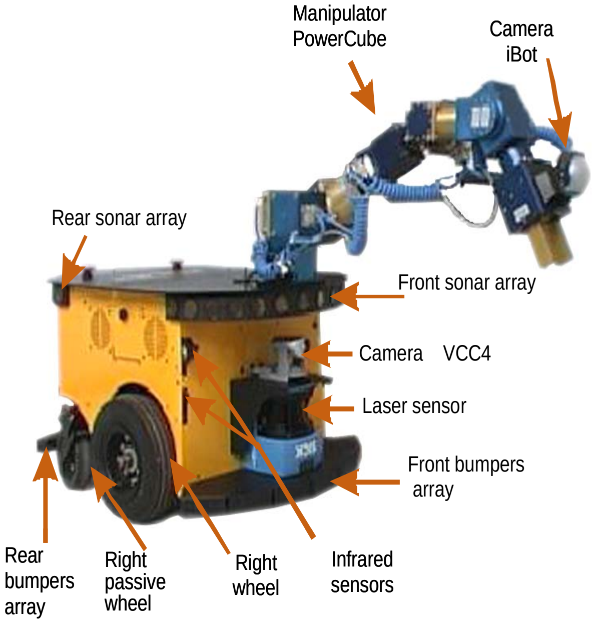


Fig. 1. Mobile robot PowerBot with industrial robot PowerCube

To realize the cooperation of different subsystems or of different sensor data processing procedures of the same subsystem it is necessary to establish the time-correspondence between data of cooperating sensors. It relates both to the synchronous and asynchronous multi-sensor systems due to the parallel manner of measurement for the sensors of different types with different time of the data processing. It is done by adding to the mentioned above local network the node that includes the timer that is used to form the labels which correspond to the instants of sensor measuring with respect to a single count time beginning. The timer is implemented in hardware [8]. It is significant that the knowledge of a current spatial state of the robot and its environment is considered the key point at creation of the intelligent environment. It explains mutual interest of the researchers working in the field of a service robotics and in the field of intelligent environments, and that considerable splash in activity of researches in the named areas, including carrying out of scientific and technical forums and occurrence of new magazines.

III. PERSONAL SERVICE ROBOTICS AND CONCEPT OF INTELLIGENT ENVIRONMENT

Today does exist many definitions of the concept of intelligent environment (intelligent space) that depend on the field of author's activity and their professional experience. We will fallow to definition of intelligent space given in [9]: “Intelligent space ... is an environmental system able to support humans in informative and physical ways”.

With respect to the notion of intelligent environment it is possible to relate personal service robots to one of the classes of the artificial systems (agents) that can be used to provide physical and informative service to humans and other artificial systems. In the same time, robots as well as humans are supported by an intelligent environment like clients. In the last case one of the principal characteristics of intelligent spaces is that robot can use them as an external sensorial system, as a source of specific useful information, and as means of communication with human and other technical systems.

One of the important characteristics of the intelligent environment is their capability to define the spatial position of human being and other mobile agents. Depending on types of the sensors used and of the architecture of the data processing system, different approaches to provide this capability exist. These approaches are based on using the sensors and sensorial systems traditional for robotics: cameras for mono and stereovision, laser rangefinders, ultrasonic and infrared sensors, tactile sensors etc. Recently iGPS systems, RFID technology (Radio Frequency Identification) and RFID-distributed networks based on this technology became the focus of researches in the field of Service Robotics and Intelligent Environment.

A number of approaches have been presented which employ the RFID technology in the projects in Intelligent Environment and Service Robotics of a different scale – from solving the navigation tasks of mobile robots to developing the concept of RobotTown with distributed sensors and RFID tags [10]- [13].

RFID technology was extensively used for development of a common platform technology for the next generation robots, particularly for creation of the Robot Town Project [14]- [17].

Some authors, especially after the appearance of RFID-technologies and RFID-distributed networks based on these technologies, propose to interpret an intelligent environment as information infrastructure of robot work place and to simplify sensorial and intelligent subsystems of robot. However, many RFID-distributed network based on these technologies, propose to interpret an intelligent environment as information infrastructure of robot work place and to simplify sensorial and intelligent subsystems of robot. However, many factors can interfere with the transmission of the radio signal, resulting in a high uncertainty of scan results. Another shortcoming is the fact that at least in the case of passive RFID tags an RFID reader can only determine whether or not a tag is in its range. Neither distance nor bearing to a recognized label are supplied. Several strategies to overcome those issues have emerged, of which an overview is given in [12]. In a word, the inaccuracy and ambiguity induced by the RFID range are the major problems of the existing RFID-based indoor mobile robot localization. At the same time RFID-based Localization techniques have a common, i.e. quickly identifying and locating each reference object by retrieving the unique ID code and location information stored in the reference object using a transceiver. We believe that an approach of using the intelligent environment for an enhancement of robot abilities to autonomous activity, not for the aim to get rid of robot sensors or autonomy, is only one that corresponds to the chief aim – creating multifunctional autonomous robots. This standpoint meets with approval of the practice – many researchers, including the authors of the Robot Town Project exploit the cooperation of RFID technology with sensors of other kinds to get reliable and accurate results.

A localization technique for indoor mobile robot navigation using a collection of laser-activated RFID tags distributed in the indoor environment and stereo vision is introduced in [18]. The robot localization is based on the principle of trilateration or triangulation. The localization system functions like an indoor GPS.

A method to estimate the bearing of a passive tag relative to a mobile robot equipped with RFID reader and antennas with cooperation of RFID and vision is presented in [19]. To solve the so-called kidnapped robot problem a landmark-based method using tag bearing information and a single visual landmark is developed.

A method of human recognition in indoor environment for mobile robot using RFID technology and stereo vision is proposed in [20]. Information of human being can be written in ID tags and used for detect the human. The proposed method first calculates the probability where human with ID tag exists and determines the ROI (Region of Interest) for stereo camera processing in order to get accurate position and orientation of human. The same method is used for indoor environmental obstacle recognition for mobile robot using RFID tags attached on obstacles. It does not need to process all image and easily gets some information of obstacle such as size, color, thus decreases the processing computation.

Another argument for using cooperation of different kinds of sensors relates to the different requirements to the accuracy of spatial state measurements in case of mobile robots and mobile robots with manipulation capacity. The actions of a manipulator are fulfilled in the space defined with regard to manipulator basic coordinate system. The mobile robot has to provide the needed accuracy of manipulator basic system location with regard to an area of interest that can be a few centimeters. After that, robot’s sensorial system has to define the relative spatial state of the object of interest with regard to manipulator basic coordinate system with the accuracy of millimeters. Accuracy of object's localization, using only RFID marks, is low to measure the spatial state of subjects of interest at use for control by manipulator actions that do necessary application of various kinds of sensors in a cooperation mode. To solve the problem we proposed to use the local infrastructure parallel to the infrastructure of environment for daily human life together with informative visual landmarks

IV. LOCAL INFRASTRUCTURE OF ROBOT ENVIRONMENT

To promote the creation and the practical use of the multifunctional personal and domestic service robots two reciprocally complementary lines of the problem solution can be combined. One is to increase the intelligent and mechanical capacities of the robot and another one is to create an infrastructure of the robot environment parallel to the infrastructure of the world of the human being to adapt the environment to the capacities of indoor service robots and in this manner to simplify the solution of the difficult scientific and technological problems related to the behavior of the robot directed to the goal in a dynamic environment. We've introduced the concept of material and informative components of the robot environment infrastructure [21].

A. Material Components of the Robot Environment Infrastructure

Material components are different in dependence on the infrastructure predestination: it can be the infrastructure of human-being (shared infrastructure), or specially designed for robot (infrastructure for coexistence), or mixed one. Material component of the infrastructure parallel to the infrastructure of environment for daily human life serves for adaptation of autonomous robot to this environment. For mobile robot it can be a wedge for threshold overcoming; for manipulator it can be a table, shelf, etc., designed with taking into account accessibility of working space.

To design the possible material component of an environment infrastructure for manipulator the model of the manipulator working space is presented by a parallelepiped with an inside 3D grid. In Fig. 2 the vertical sections of parallelepiped for vertical and horizontal gripper orientations are presented. The space of admissible movement of the gripper in a vertical plane is shown as vertical continuous segments. The working space for vertical gripper orientation is not the same as for horizontal orientation. The user can define the horizontal section of the working volume, like rectangles in of the manipulator working space shown in Fig. 3, where the manipulation objects can be picked up-and-placed. Material infrastructure components corresponding to manipulator working space for vertical and for horizontal gripper orientation are shown in Fig. 4.

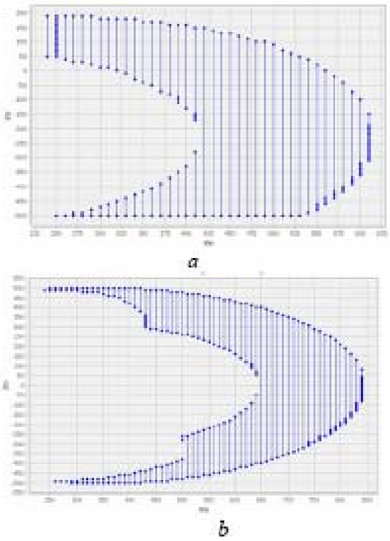


Fig. 2 Scope depth: *a* - for vertical, *b* – for horizontal gripper orientation

The space of admissible movement of the gripper in a vertical plane is shown as vertical continuous segments. The working space for vertical gripper orientation is not the same as for horizontal orientation. The user can define the horizontal section of the working volume, like rectangles in of the manipulator working space shown in Fig. 3, where the manipulation objects can be picked up-and-placed. Material infrastructure components corresponding to manipulator working space for vertical and for horizontal gripper orientation are shown in Fig. 4.

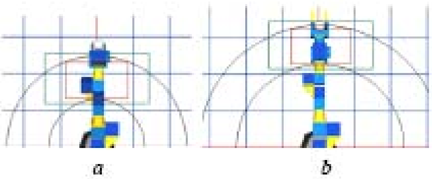


Fig. 3 Versions of the horizontal section of the manipulator working space: a – for vertical, b – for horizontal gripper orientation

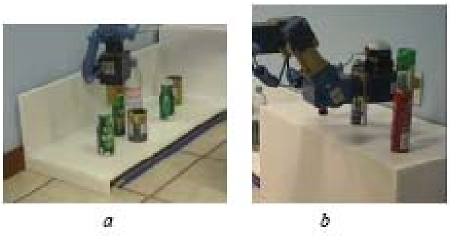


Fig. 4 Material infrastructure components corresponding manipulator working space: *a* – for vertical, *b* – for horizontal gripper orientation

We introduce the artificial informative visual landmark that allows the robot to define its 3D position and orientation with respect to the landmark 3D coordinate system using visual sensor based on a calibrated mono-camera fixed on the manipulator gripper, is presented in [22]. The position and orientation of 3D coordinate system of the manipulator working space is defined with respect to the same landmark coordinate system. It allows the manipulator visual sensor to determine the position and orientation of the working space coordinate system with respect to the manipulator coordinate system.

B. Material Components of the Robot Environment Infrastructure based on the Informative Artificial Visual Landmark

Artificial landmark-based navigation in unstructured environment is a topic of intensive investigation. There are different physical types of artificial landmarks used for terrestrial, underwater and aerial robots navigation.

Artificial landmarks, adopted to distinguish by visual sensors, presented in self-similar patterns, invariant to scaling, rotation, and viewing angle can serve as artificial landmarks whose detection indicates the presence of a landmark. The notion of self-similar landmarks (SSL) was first used in a robotic context in [23]. Self-similar landmark consist of a self-similar intensity pattern coupled with a barcode for unique identification. The author's objective was to develop planar targets that would be detected easily with a standard perspective camera on a mobile indoor robot and can be used as a beacon.

Robust vision based target recognition by presenting a novel scale and rotationally invariant target design based on SSL was introduced in [24]. The authors designed a circular landmark where the intensity is self-similar and anti-similar in all directions. They proposed a circular 3-pattern SSL target to estimate the robot pose, but as it is well known and is mentioned by the authors, at most 8 poses will be consistent with such target observation.

Mostly these types of landmarks serve to robot to define the directional information. Some of proposed visual landmarks allows the robot to define de direction and distance to the mark [25].To define robot location a set of landmarks is used, if the unique landmark is not used like a beacon.

Visual landmark with memory storage consisting of landmark part and memory part was proposed in [26]. The landmark part is to be estimated the relative pose between a camera on the robot (mobile manipulator) and the landmark. The memory part consists of QR code, which is kind of two-dimensional bar codes, and contains such information as object identification, what tasks there are, and how to conduct the tasks. A code reader is utilized to read bar code data. The pose measurement part consists of a CCD camera, a lightning system and image processing system placed on the manipulator. The marks for self-positioning are adequately disposed in the working environment. The marks for manipulation are attached to all the objects of interest. The knowledge of the relative pose between a camera on the robot and the mark, allows the robot to know the relative pose of the object from the robot by measuring relative pose of the mark from the robot.

The informative visual landmark developed by us could be easily detected and identified by the mono-camera visual sensor, which uses a calibrated camera with corrected radial distortion [22]. In the style of using the visual landmark for informative support of autonomous robot action our proposal is close to presented in [26]. The difference is in the principles of landmark construction and visual system functioning, in applicability of our landmark for maintenance both mobile robots and manipulator, in the operative record of the information about the current spatial state of the object of interest and additional specific information about what tasks there are and how to conduct these tasks.

Our landmark is multifunctional in sense of its applicability both for mobile robots pose definition and for control by manipulators with changeable base position. The landmark identification, based on the calculation of the landmark characteristics, allows the robot, behind the definition of its spatial state, to record and use some additional, specific for this landmark, information about robot environment and about what tasks there are and how to conduct these tasks.

The visual landmark proposed is presented by the vertices of a convex flat quadrilateral (not necessarily rectangular) with two parallel sides of known length. Due to the fact that landmark's geometrical characteristic such as convexity is invariant to perspective transformation, the proposed landmark is insensitive to the variations in position, size, orientation, and distance in the range of the camera's visual field depth.

The quadrilateral can be both natural and artificial. There are different kinds of an artificial landmark's vertices presentation such as centroids of isolated regions of a given form and size, points of intersection of line segments, two of which have to be parallel. An example of the landmark diagram with vertices presented by centroids of the circles of different diameters is shown in Fig. 5.

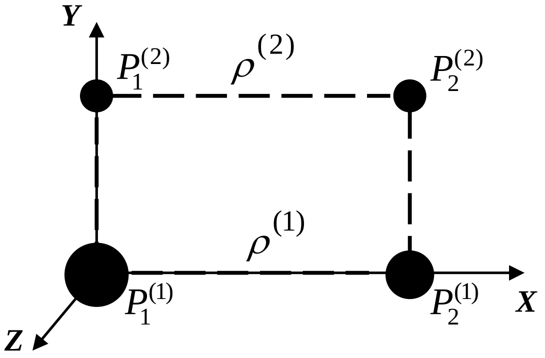


Fig. 5. Landmark diagram with vertices presented by centroids of the circles of different diameters

Four vertices found during the image processing are putting and numbered in order against the hands of a clock with respect to a distinguished vertex used as the origin of landmark's coordinate system. Distinguished vertex can be marked in different ways depending on the kind of vertex presentation, e. g., with the specific size of the landmark subtarget - the circle of the maximal size in Fig. 5, with an additional subtarget as the distinguished vertex pointer in Fig. 6, with different colors, etc.

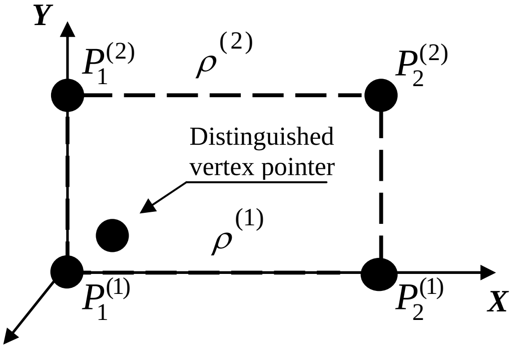


Fig. 6. Landmark diagram with vertices presented by centroids of the circles of the same diameters and with an additional circle as the distinguished vertex pointer (the most close to the distinguished vertex)

Two pairs of vertexes (the first and second ($P_1^{(1)}$ and $P_2^{(1)}$) and the third and fourth ($P_2^{(2)}$ and $P_1^{(2)}$)) form the parallel sides of the quadrilateral. The second vertex $P_2^{(1)}$ is a point on abscissa of the landmark's coordinate system and is used for calculating the abscissa unit vector. In case of perpendicularity of the line segment formed by the first and the fourth vertexes to the line segment formed by the first and the second vertexes the fourth one $P_2^{(2)}$ is used for calculating the ordinate unit vector. The applicate unit vector is calculated as vector crossproduct of the unit vectors of abscissa and ordinate. If the mentioned condition of perpendicularity is not satisfied, the applicate unit vector is calculated as the unit normal to the plane that contains mark vertexes. In this case the ordinate's unit vector is calculated as vector cross-product of the unit vectors of applicate and abscissa.

C. Calculating the Three-Dimensional Coordinates of the Landmark Vertices

The 3D coordinates of the mark vertices are calculated as coordinates of the terminal points of two parallel line segments with the known lengths. The coordinates are calculated using the results in perspective projection geometry presented in [27].

The 3D coordinates are defined with regard to the system of coordinates of the camera with the origin in the main point (the perspective projection center) and with the axis Z parallel to the optical axis of the camera lens. The distortion of the image grasped by the camera is corrected.

For the j-th line segment, j = 1, 2, the 3D coordinates of the terminal points are calculated as

$$X_1^{(j)} = Z_1^{(j)} \frac{x_1^{(j)}}{f}$$

$$Y_1^{(j)} = Z_1^{(j)} \frac{y_1^{(j)}}{f}$$

$$Z_1^{(j)} = \frac{\rho^{(j)} \left[\left(fb_1 - b_3 x_2^{(j)} \right) \delta x^{(j)} + \left(fb_2 - b_3 y_2^{(j)} \right) \delta y^{(j)} \right]}{\left(\delta x^{(j)} \right)^2 + \left(\delta y^{(j)} \right)^2}$$

where

$$X_2^{(j)} = X_1^{(j)} + \rho^{(j)} b_1$$

$$Y_2^{(j)} = Y_1^{(j)} + \rho^{(j)} b_2$$

$$Z_2^{(j)} = Z_1^{(j)} + \rho^{(j)} b_3$$

where $\left(X_1^{(j)}, Y_1^{(j)}, Z_1^{(j)} \right)$ y $\left(X_2^{(j)}, Y_2^{(j)}, Z_2^{(j)} \right)$ represent the coordinates of the terminal points $P_1^{(j)}, P_2^{(j)}$ of the line segment j;

$\left(x_1^{(j)}, y_1^{(j)} \right), \left(x_2^{(j)}, y_2^{(j)} \right)$ are the coordinates of the projections of the terminal points of the line segment j in the image plane;

$\rho^{(j)}$ is the length of the j-th line segment;

b_1, b_2, b_3 are direction cosines of the line segments (the same for parallel line segments)

f is the focus of the pin-hole camera model.

Direction cosines of 3D line segment in a vector notation are calculated as

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \pm \frac{\begin{pmatrix} c_2^{(1)} f \\ -c_1^{(1)} f \\ y_1^{(1)} c_1^{(1)} - x_1^{(1)} c_2^{(1)} \end{pmatrix} \times \begin{pmatrix} c_2^{(2)} f \\ -c_1^{(2)} f \\ y_1^{(2)} c_1^{(2)} - x_1^{(2)} c_2^{(2)} \end{pmatrix}}{\left\| \begin{pmatrix} c_2^{(1)} f \\ -c_1^{(1)} f \\ y_2^{(1)} c_1^{(1)} - x_1^{(1)} c_2^{(1)} \end{pmatrix} \times \begin{pmatrix} c_2^{(2)} f \\ -c_1^{(2)} f \\ y_1^{(2)} c_1^{(2)} - x_1^{(2)} c_2^{(2)} \end{pmatrix} \right\|}$$

where $\left(c_1^{(1)}, c_2^{(1)} \right) y \left(c_1^{(2)}, c_2^{(2)} \right)$ are the direction cosines of the projection of parallel line segments 1 y 2 respectively that are calculated as

$$c_1^{(j)} = \frac{x_2^{(j)} - x_1^{(j)}}{M_j}, \quad c_2^{(j)} = \frac{y_2^{(j)} - y_1^{(j)}}{M_j}, \quad j = 1, 2$$

where $M_j = \sqrt{(x_2^{(j)} - x_1^{(j)})^2 + (y_2^{(j)} - y_1^{(j)})^2}$.

D. Matrix of transformation from the mark's coordinate system to the camera's coordinate system and inverse one

The origin of the mark's coordinate system with regard to the camera's coordinate system coincides with the distinguished vertex $P_1^{(1)}$ and has the coordinates $\left(X_1^{(1)}, Y_1^{(1)}, Z_1^{(1)}\right)$. The unit vectors of the coordinate axis in case of perpendicularity of the segment of terminal points $\left(P_1^{(1)}, P_1^{(2)}\right)$ to the segment $\left(P_1^{(1)}, P_2^{(1)}\right)$ are:

$$
\begin{aligned}
{}^C\hat{x}_m &= \left(b_1, b_2, b_3\right)^T \\
{}^C\hat{y}_m &= \frac{1}{M^{(Y)}}\left(X_1^{(2)} - X_1^{(1)}, Y_1^{(2)} - Y_1^{(1)}, Z_1^{(2)} - Z_1^{(1)}\right)^T \\
{}^C\hat{z}_m &= {}^C\hat{x}_m \times {}^C\hat{y}_m
\end{aligned}
$$

where

$$M^{(Y)} = \left((X_1^{(2)} - X_1^{(1)})^2 + (Y_1^{(2)} - Y_1^{(1)})^2 + (Z_1^{(2)} - Z_1^{(1)})^2\right)^{\frac{1}{2}}$$

In case of not perpendicularity of the segment of terminal points $\left(P_1^{(1)}, P_1^{(2)}\right)$ to the segment $\left(P_1^{(1)}, P_2^{(1)}\right)$ the unit vectors of the coordinate axes are:

$${}^C\hat{x}_m = \left(b_1, b_2, b_3\right)^T$$

${}^C\hat{z}_m$ is calculated as the unit vector that coincides with normal to the plane that passes via the vertices $P_1^{(1)}, P_1^{(2)}$, and $P_2^{(1)}$.

$${}^C\hat{y}_m = {}^C\hat{z}_m \times {}^C\hat{x}_m$$

The homogeneous transformation matrix from the mark's coordinate system to the camera's coordinate system is:

$${}^C T_m = \begin{bmatrix} {}^C\hat{x}_m & {}^C\hat{y}_m & {}^C\hat{z}_m & {}^C P_1^{(1)} \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

where ${}^C P_1^{(1)}$ is the vector that defines the position of the first (distinguished) vertex with regard to the camera's coordinate system.

The matrix ${}^m T_C$ that defines the transformation from camera's coordinate system to the mark's coordinate system is calculated as inverse matrix ${}^C T_m^{-1}$.

The software that implements the described method and experimental investigations were fulfilled by Dante Raúl Vásquez-Hernández.

In the first experimental version, a landmark was composed of four circles (subtargets) that form a rectangle with known side length. The combinations of the sizes of corresponding subtargets, the distances between some of subtargets as well as the color of subtargets and background can serve as a landmark identifier. The selection of circles is not critical. Various types of the principal subtargets, which form the convex quadrilateral, and some additional subtargets, like the circle-pointer of the distinguished vertex (Fig. 6), can be used. The visual landmark with principal line subtargets of different colors is presented in Fig. 7. It is combined with an additional subtarget, which is a self-similar landmark used for fast searching the location of the principal subtagets.

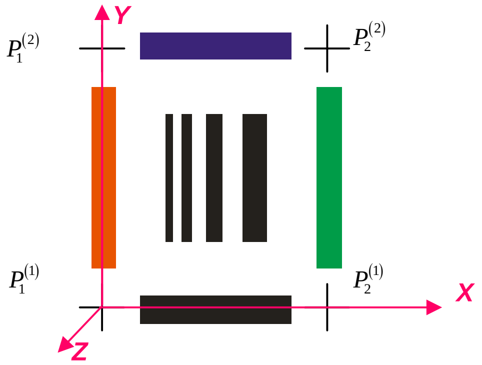


Fig. 7. Landmark with the principal subtargets of different colors combined with self-similar landmark

Self-similar landmark can be used both for proposed landmark's localization in case of its application jointly with our informative visual landmark, or independently as a version of presentation of the landmark's four vertexes. In the last case the self-similar landmark's parallel bars can be used to form the parallel segments of known length. The problem of mark's identification can be solved using different colors or the binary barcode proposed in [23].

Depending on version of landmark, the algorithm of image processing defines 3D coordinates of the circle centroids (Fig. 5, Fig. 6), of the points of intersection of line segments (Fig. 7) or of the vertices of selected line segments of the self-similar landmark with respect to the camera coordinate system. These data are used for direct pose calculation.

E. Applicability of the Informative Visual Landmark for Control by a Mobile Robot with Manipulator

There are various kinds of application of the multifunctional informative landmark for control by mobile robot with manipulator. Common for all of them is the cooperation of robot sensor systems. Robot sensors provide functions based on position information. Control by the robot action starts with the assumption of exact knowledge of the initial pose of a mobile robot with regard to world coordinate system. The odometry sensors are used as metric reference. Due to the direct pose estimation landmarks can be used for correction of the trajectory deviation provoked by the cumulative error typical for dead-reckoning navigation. Collaborative sensors data processing is also used to cut down analyzed space of scene by directed selection of the area of landmark location.

For known spatial state of the landmark with respect to a global coordinate system, robot can define its global position and orientation. For mono-camera-based visual system mounted on the robot there are two main versions of the landmark location in indoor scene - distributed and centralized. In accordance to distributed version the landmarks are located along the routes of mobile robot movement, on goal objects and obstacles. Centralized location is used for landmark visible from a large area of the possible robot locations as in case of the landmark mounted on the ceiling. Using wireless communication the multifunctional service robots can share with each other the data about their poses with respect to the world coordinate system that allows them to calculate the spatial position with respect to each other and its change in time.

Mounting landmark on the robot and using a network of external cameras will make it possible to solve the same navigation problem for closed areas, as it is solved by the GPS navigation systems for open areas. The external cameras network can be used to organize a cooperative dynamic behavior of a family of service robots.

The particular data that relate to each landmark in correspondence with its identification contain the information like a tag of the area of the landmark location including metric map of the nearest surroundings. It allows us to combine topological and metric maps that can simplify the task of service autonomous robot navigation and docking at objective places.

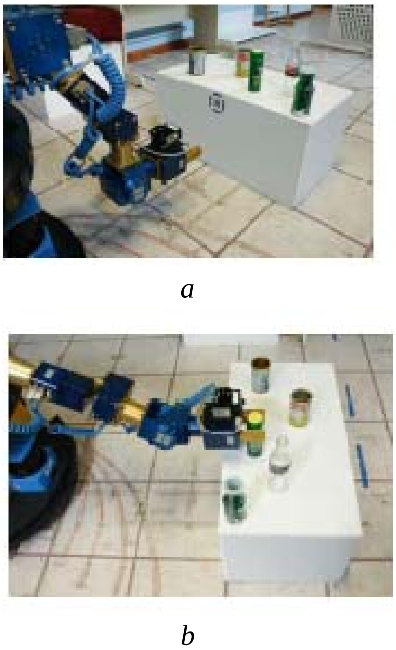
Additional information associated with the landmark and recorded in robot memory can be used for goal directed actions planning. It is a substantiation to name the offered type of mark "informative mark". Combined with guide marks of a human being infrastructure, this type of landmarks would serve for both communities - of human being and robot (Fig. 8).

Fig. 8 Landmark combined with guide.

In application of the proposed landmark for control by manipulator with changeable base position, the spatial state of some object known with respect to the robot coordinate system can be calculated with respect to the landmark coordinate system. In the same time, if the spatial state of some object is known with respect to the landmark coordinate system it is possible to calculate the spatial state of this object with respect to the robot coordinate system. After the next arriving to manipulate by this object robot can recalculate object space position from mark coordinate system to the new position of robot coordinate system. This capability can be used for providing cooperative acting the team of the multifunctional service robots allowing them by means of the wireless communication to share with each other the recorded data about the spatial position of the objects with respect to the landmark coordinate system.

It is also promising opportunity to use one of the cameras of a stereo system for perception of the offered informative artificial visual landmark to select the area of searching the obstacles in the closest of the object surroundings, chosen for grasping by manipulator.

Some robot-manipulator actions with application of the informative visual landmark are illustrated below. The initial and final phases of object grasping in case of the application of the landmark common for the whole of manipulator working space are shown in Fig. 9. The same phases in case of the application of the individual landmarks attached to each object of manipulation (individual object or container for objects) are shown in Fig. 10. The landmark, common for the whole of manipulator working space, serves also as the informative visual landmark for mobile robot.



a

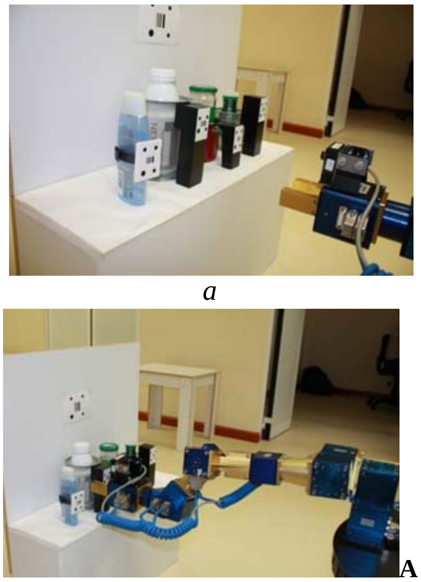
b

Fig. 9. Robot actions with application of the common informative visual landmark a - pose definition using landmark, b - object grasping

F. *Constructing Canonic and Convergent Stereo Systems from off-the-Shelf Cameras Using Robotics Tools*

As pointed out above, it is promising opportunity to use one of the cameras of a stereo system for perception of the offered informative artificial visual landmark to select the area of analysis of the spatial state of the surroundings nearest to landmark. Computational stereo vision is an important cue for robotics. It can be used for objects shapes and pose recognition in the task of vision-guided navigation and manipulation. Besides this area of application a large number of important applications such as surveying and mapping, engineering, architecture, involve quantitative measurements of coordinates of 3D points from stereo pair images .

The cost of a stereoscopic system has an influence on its application. In the current work we present the means to construct both the canonic and convergent stereo systems.



a

b

Fig. 10. Robot actions with application of the individual informative visual landmarks: a - pose definition using landmark, b - object grasping

The main attention is paid to solve the problem of correction of the intrinsic characteristics of the cameras to reach acceptable exactitude of stereo measuring.

There are two types of stereoscopic systems – the parallel, which has parallel optical cameras axes, and the convergent one. Simpler in the sense of the number of operations for the calculations of the three-dimensional coordinates is the parallel system. When the planes of images of two cameras coincide, the cameras have the same focal length, and the corresponding scanning lines coincide, such a system is a canonic stereoscopic system. In this case for each point in one image, its corresponding point in the other image can be found by looking only along a corresponding horizontal line. The simplification of the calculations is an obligatory condition to construct the real-time systems of stereoscopic vision.

The developed robotics tools are destined to construct. The method of constructing the low cost canonic and convergent stereo systems using off-the-shelf cameras is based on the simultaneous individual calibration of every camera using the same mask. To adjust a camera with regard to other one a manipulator of 6 degrees of freedom is used. The developed software allows us to realize the change of the position and orientation of the camera in an automatic way. Using the calibration system the developed tools are applicable for examination and equalization of the focal lengths of two cameras of the stereo system under constructing and also of the cameras of ready stereo systems. As the mechanism to construct the stereo systems the manipulator PowerCube is used.

For cameras calibration we use the well known Tsai method [28] that allows us to find the extrinsic and intrinsic parameters of each of the cameras by processing the images of the flat mask (coplanar calibration) or the images of a sequence of parallel flat masks located on the different known distances from an initial plane (no coplanar calibration).

Fig. 11 Tools (hardware) for constructing canonic and convergent stereo systems

In the result of calibration of two cameras with the same mask the matrices of transformation between the mask coordinate system (M) and coordinate systems of the left (L) and right (R) cameras ${}^{M}T_{C_L}$ and ${}^{M}T_{C_R}$ are known. So, it is possible to find the space relations between two cameras:

$$ {}^{C_L}T_{C_R} = {}^{C_L}T_M \, {}^{M}T_{C_R} $$

To define if the requirements mentioned are satisfied the expression of the matrix ${}^{C_L}T^{can}_{C_R}$ for the canonic stereoscopic system is used

$$ {}^{C_L}T^{can}_{C_R} = \begin{bmatrix} 1 & 0 & 0 & B \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

where B denotes the base distance (distance between optical centers of the pin-hole camera models).

The problem of fitting two cameras to receive the canonic stereoscopic system is fulfilled by the movement by manipulator of a movable camera C_R with respect to the immovable camera C_L that provides the correspondence to the matrix ${}^{C_L}T^{can}_{C_R}$. The movable camera C_R is rigidly fixed by the gripper of the manipulator. The relation between the coordinate system of the camera and the coordinate system of the gripper is received by the calibration of the camera-gripper system. Before realizing this calibration the relations between the mask coordinate system and the manipulator basic coordinate system are defined and used for calculation of the desired spatial state of the gripper with camera. The details are presented in [29].

After fixation of the fitted cameras rigidly each to another and release movable camera from the gripper and immovable one from its supporting device, canonic stereoscopic system is constructed and again its resultant matrix ${}^{C_L}T^{res}_{C_R}$ is calculated. An example of such matrix for canonic stereo system constructed with cameras DCAM with focus 2.9 mm. is presented below:

$${}^{C_L}T^{res}_{C_R} = \begin{bmatrix} 0.999997 & -0.002282 & 0.000316 & 124.517 \\ 0.002282 & 0.999998 & -0.000342 & -0.015927 \\ -0.000315 & 0.000343 & 1.0 & 0.062144 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The upper left 3×3 submatrix represents the rotation of the right camera coordinate system and the upper right 3 1 × submatrix represents the position vector of the origin of the right camera coordinate system with respect to the left camera coordinate system.

It is visible that the matrix ${}^{C_L}T^{res}_{C_R}$ differs from the matrix ${}^{C_L}T^{can}_{C_R}$. The difference in orientation is depreciatingly insignificant. The base distance is 124.517 mm. The right camera origin is pulled down along the ordinate axis at -0,016 mm. that corresponds to 2.88 pxs. The displacement along the optical axis is 0.062 mm. that corresponds to about 2% of the focal length that is acceptable for such kind of stereo systems. It is necessary to take into account the displacement of the right image along the ordinate axis by bringing the left camera scan line in correspondence with displaced at 3 pxs the corresponding right camera scan line.

Because the formulas of the of spatial coordinates calculation corresponds to the ideal cameras it is necessary to provide the correction of distortion of the cameras lenses using the value of lens distortion coefficient received from camera calibration. To carry out it, we use the method of bilinear interpolation with taking into consideration the possibility of real-time realization by using the FPGA technology [29].

To transform the stereo system from a canonic mode to a convergent one it is sufficient to rotate the vector ${}^{C_L}\vec{B} = (B, 0, 0)^T$, that represents the stereo system base, together with the camera C_R about the Y_{C_L} axis of the camera C_L with θ convergence angle. The transformation matrix that relates the right camera to the left one is:

$${}^{C_L}T^{conv}_{C_R} = \begin{bmatrix} \cos\theta & 0 & \sin\theta & B\cos\frac{\theta}{2} \\ 0 & 1 & 0 & 0 \\ -\sin\theta & 0 & \cos\theta & B\sin\frac{\theta}{2} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The convergent stereo system received has the same base distance as canonic one. The details are presented in [30]. The software that implements the described method and experimental investigations were fulfilled by Ismael de Jesús Pérez-Velasco.

V. CONCLUSION

The Distributed Architecture Centralized by Knowledge permits us to realize the cooperation of various subsystems that provides the robot autonomous functioning. The knowledge of a current spatial state of the robot and its environment is considered the key point at creation of the intellectual environment. So, this architecture can be easily integrated with the architecture of intelligent environment both as an agent o as a master that uses the environmental support.

To promote the creation and the practical use of the multifunctional personal and domestic service robots the concept of material and informative segments of the robots infrastructure have been introduced. The infrastructure can be the infrastructure of human-being (shared infrastructure), or designed only for robot (infrastructure for coexistence), or mixed one. Informative components are mostly robot-oriented. The proposed material segment of the robots infrastructure is a tool destined for adapting the environment to the capacities of service robots. As an informative segment of the robots infrastructure multifunctional visual informative landmark and mono-camera-based vision system adjustable with stereo system. It allows the robot to define its position and orientation in 3D space with respect to the landmark coordinate system and, by this way, with respect to a global coordinate system. It allows us to realize an environment model representation as a hybrid of topological and metrical maps. It is applicable both for mobile robots and for robots-manipulators. The offered means allow us to approach time of creation and practical application of multi-purpose service robots. The future work will be directed to solving the problems of development of information support of multifunctional personal robots and to creating a parallel robot world and adjusting it with human being world.

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