FACTA UNIVERSITATIS
Series: **Mechanics, Automatic Control and Robotics** Vol. 6, Special Issue, 2007, pp. 111 - 122

USING BINOCULAR STEREOVISION FOR CALCULATING MOTION REFERENCES FOR A MOBILE MANIPULATOR

UDC 62-236.58:531.35/.37(045)=111

Levent Çetin, Erol Uyar

Dokuz Eylül University, Mechatronics Laboratory,
Bornova, 53100 Izmir, Republic of Turkey
e-mail: levent.cetin; erol.uyar @deu.edu.tr

Abstract. *This paper focuses on the design and application of a stereo setup that is mounted on a mobile manipulator. This setup is utilized to generate reference points for mobile manipulator, dynamically. Tasks, 3D recovery and feature extraction are accomplished in camera reference frames then they are transformed to robot coordinate frame. Recovered position data is converted to manipulator pose with two-stage algorithm: an iterative approach for positioning and inverse kinematics calculations for orientation requirement. A computer application of this algorithm is developed and tested for position control of mobile manipulators with active vision.*

Key words: *Stereo Vision, Inverse kinematics, Mobile manipulator*

1. INTRODUCTION

A mobile manipulator consists of an articulated arm mounted on a mobile platform. Since this mechanical arrangement combines the dexterity of the former with the workspace extension of the latter, it is clearly appealing for many applications [1]. Wheeled Mobile Robot is defined as a wheeled vehicle which is capable of autonomous motion because it is equipped with an embarked computer [2]. It should be added to this definition that the vehicle is also equipped with sensors to perceive about the environment [3].The mobile part of mobile manipulator has smaller control space compared with configuration space and this causes conditional controllability of these systems [4]. Many studies in nonholonomic control systems have been carried on in past decades [5]. But universal control methodology has not been developed even for a simple differentially driven mobile platform. These limitations can be overcome by either relaxing the constraints on desired pose, i.e. stabilizing to a point without a guarantee on orientation [6].Manipulator part of mobile manipulator does not subject to any kinematical constraint. Therefore design methodologies referring to inverse and forward representation of kinetics are exploited in control strategies. Detailed explanation of various control schemes can be found in standard robotics text books [7].

Received December 20, 2007

Control of the mobile manipulators is generally based on combined kinematical analysis of the both subsystems. [8]. Developed methodologies for computing actuator commands for such systems allow them to follow desired end-effector and platform trajectories without violating the nonholonomic constraints. Human capability to control his movements exploiting visual perception creates challenging research fields to control articulated robots. Because robotic hand eye coordination should ideally be flexible and effective while retaining the power of the machines.

This paper describes an alternative pragmatic approach to generate reference for a mobile manipulator, which is a differential drive equipped with 2DOF planar manipulator. Our goal is to develop relatively fast application for enabling computer systems with relatively slow configuration is to be used in visual control loops. Primary issue on this research is to obtain an algorithmic layout for well-known theory by taking constraints arising from real time application into account. In the context of this paper a dynamic look and move system considered and a computational method relating image data from cameras to robot link variables are developed. 3D recovery with stereovision is the first stage of the task. This problem is solved by taking non parallel left and right camera axis into consideration and resultant equations results in robot manipulator base coordinates. Conversion from task space which is observed with stereo setup to configuration space is done not in conventional way like homogenous transformations but in a more task specific way with following steps: (i) calculate link parameters from z coordinate of target (ii) Solve cart position reference and orientation reference via x,y of target and link references found in step(i). (iii) Solve gripper pose with orientation data from image. By using extrinsic camera calibration data and iterative approach to position equations, a more reliable application than direct implementations of basic equations is obtained In the following sections first derivation of algorithm is represented. Afterwards an implementation layout and demographic results are given.

2. PROBLEM DEFINITION

As described in first section of the paper, mobile manipulators are systems which are combination of two subsystems: A 2 degrees of freedom planar arm and a gripper as manipulator part and a differentially driven platform. Overall system possesses 7 degrees of freedom with 6 actuator inputs. This paper deals with question: with a given task, grasping an observed object, what are the actuator references to track to succeed task? Concerning necessity of external feedback for nonholonomic mobile platform control a stereo setup for recovering 3D target position is introduced. Attaching this stereo rig on mobile platform helps to recover error posture (reference) for mobile platform motion controller.

3. KINEMATICS OF MOBILE MANIPULATOR

Kinematics of differentially driven autonomous vehicles and manipulators can be found in standard robotic text books. Derivations of equations, represented in this section, are through geometrical relations which are arising from structure of the mobile manipulator.

A mobile platform, which is located on 2D plane, possesses 3 degrees of freedom in the world coordinates

$$p_v = \begin{bmatrix} x_v \\ y_v \\ z_v \end{bmatrix} \tag{1}$$

This posture, p_c, represents planar position and robot orientation in a right handed coordinate frame. For a given path in a plane, posture p is a function of time and follows entire locus of point $[x_v(t)\ y_v(t)]^T$. If time derivatives of trajectory points exist, then $\theta_v(t)$ is not an independent variable.

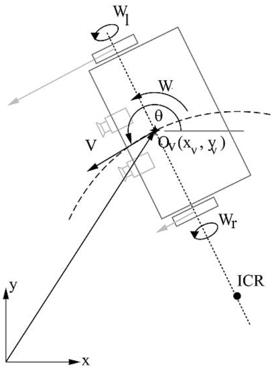

Fig. 1. mobile platform pose in plane

Motion of the differential drive platform is governed via linear velocity and rotational velocity, which are also functions of the time. The vehicle kinematics is defined with equation:

$$\begin{bmatrix}\dot{x}_v\\ \dot{y}_v\\ \dot{\theta}_v\end{bmatrix} = \dot{p}_v = J_v\dot{q}_v = \begin{bmatrix}\cos\theta & 0\\ \sin\theta & 0\\ 0 & 1\end{bmatrix}\begin{bmatrix}v\\ w\end{bmatrix} \tag{2}$$

Task space velocities and control space velocities are converted to each other with given Jacobian matrix (J_v). Control space velocities are translational velocity of mobile platform and angular velocity, it pivots. These two velocities are related to wheel velocities with given constructive parameters (figure 2&3):

$$\begin{bmatrix}v\\ w\end{bmatrix} = \frac{1}{R}\begin{bmatrix}1 & 1\\ L & -L\end{bmatrix}\begin{bmatrix}w_l\\ w_r\end{bmatrix} \tag{3}$$

Concerning two control signals translational velocity and rotational velocity, two positional references are considered to guide mobile platform to desired position. These are approach distance, d_1, and rotation of angle θ_1.

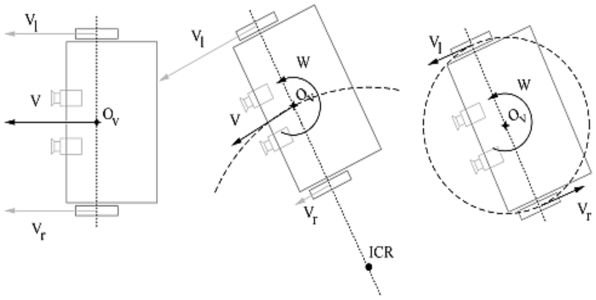

Fig. 2. Mobile platform motion concerning wheel velocities

From manipulator point of view, there are two geometric relations to solve position reference problem, these are gripper pose and manipulator pose. Inverse kinematics solution is decomposed in to three stages .The first two joint axes actuated in relation with positional references θ_2, θ_3. The third link compensates z axis orientation error θ4. The last link sets gripper orientation parallel to target object orientation θ5.

It is seen from the related transformation matrix that the two link manipulator is highly deficient and can only track points in XY plane which are within the maximum reach pose.

Inverse kinematics task is to find joint variables to position end point of two link arm (which is referred as wrist centre). Using geometrical relations according to target position ($P_t=[x_t\ y_t\ z_t]^T$) concerning structure of robot, implicit expressions representing arm pose are found as following:

$$\theta_1 = a\tan 2(y_t, x_t) \tag{4}$$

$$l_2 \sin\theta_2 + l_3 \sin(\theta_2 + \theta_3) = z_t \tag{5}$$

$$d_1 + l_2 \cos\theta_2 + l_3 \cos(\theta_2 + \theta_3) = x_t^* \tag{6}$$

x_t^* is a modified position coordinate of target point. Definition and solution of this value is expressed in following section.

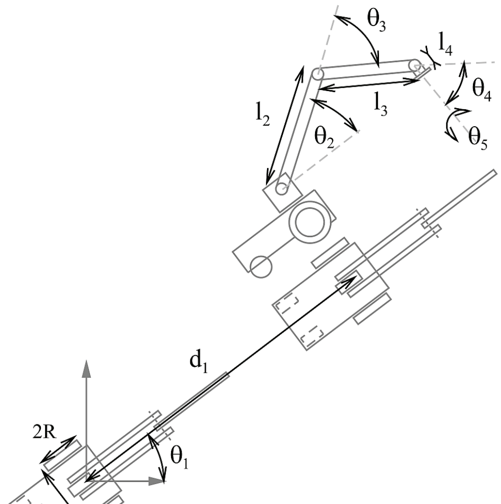

Fig. 3. Mobile manipulator motion parameters

It is seen from the related transformation matrix that the two link manipulator is highly deficient and can only track points in XY plane which are within the maximum reach pose.

x_t^* is a modified position coordinate of target point. Definition and solution of this value is expressed in following section.

Task is complicated because of the redundancy in mechanism. Translational motion of the mobile platform changes the wrist position reference for inverse kinematics solution. This specific coincidence results infinite number of solutions according to kinematical redundancy.

Before solving inverse kinematics for robotic arm, it is necessary to solve grasping form. The orientation of the gripper is found based on visual features of target. The third joint angle is found according to shape of the target. If the shape is compact, normal of image plane is aligned with normal axis of end effector coordinate frame (Equation 7). If it is like rectangular in shape then normal of image plane is aligned with approach axis of end effector coordinate frame (Equation 8).

Solution for θ_4 is done using right angled trapezoid formed by robot manipulator. Firstly exploiting the fact that sum of inner angles of closed polygon with for corners is equal to 2π, constraint for θ_4 is found. Afterwards explicit equations are given respectively for the situations corresponding to given conditions:

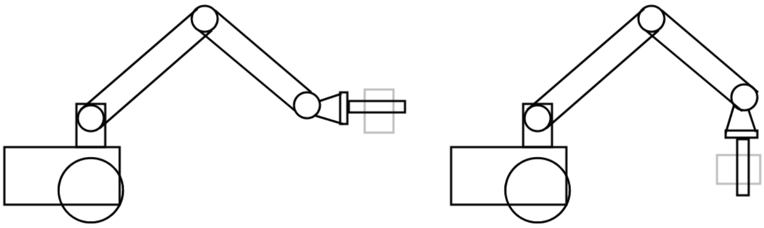

Fig. 4. Two gripping configurations corresponding to shape of target

$$\theta_2 + \pi - \theta_3 + \pi - \theta_4 + \frac{\pi}{2} = 2\pi \tag{7}$$

$$\theta_4 = \frac{\pi}{2} + \theta_2 - \theta_3 \tag{8}$$

$$\theta_4 = \theta_2 - \theta_3 \tag{9}$$

The first step to derive information about orientation is to construct a covariance matrix using the second order central moments. Hence, it follows:

$$\operatorname{cov}[I(i,j)] = \begin{bmatrix} \mu'_{20} & \mu'_{11} \\ \mu'_{11} & \mu'_{02} \end{bmatrix} \tag{10}$$

The eigenvectors of this matrix correspond to the major and minor axes of the image intensity. Thus, the orientation can be extracted from the angle of the eigenvector associated with the largest eigenvalue. The angle, θ_5 is given by the following formula:

$$\theta_5 = \frac{1}{2}\tan^{-1}\left(\frac{2\mu'_{11}}{\mu'_{20} - \mu'_{02}}\right) \tag{11}$$

Eventually, all of the necessary variables are solved throughout calculations either through trigonometric equations, iterative calculations or tools for image level calculations.

According to shape of the target grasping form is determined. If target is compact, wrist position (P_w) is calculated as in equation x whereas if not compact, it is calculated as equation y.

$$P_w = \begin{bmatrix} \sqrt{x_t^2 + y_t^2} + l_4 \\ z_t \end{bmatrix} \tag{12}$$

$$P_w = \begin{bmatrix} \sqrt{x_t^2 + y_t^2} \\ z_t + l_4 \end{bmatrix} \tag{13}$$

It is seen from derivations that for solving d_1, θ_2, θ_3 there are two equations. Distance d_1 cannot be obtained directly from straightforward distance calculation because mobile platform must be placed relative to the target with a distance according to manipulator pose. Consequently, necessary pose of the planar manipulator to obtain desired end effector position and orientation must be calculated. However this situation causes an ambiguity in calculation since distance from robot coordinate frame origin to target is necessary for solving both manipulator pose and mobile platform positioning. Therefore an iterative approach is developed to solve equation 5, which searches manipulator pose, is implemented to position the end effector at z_t, and to align end effector relative to target. Equation 6 is rearranged to find d_1:

$$d_1 = x_w - (l_2 \cos\theta_2 + l_3 \cos(\theta_2 + \theta_3)) \tag{14}$$

All the equations are derived in robot manipulator base coordinate system. In the following a vision based algorithm is introduced to find target point in the same coordinate system.

3. STEREO VISION CALCULATIONS BASED ON HOMOGENOUS TRANSFORMATIONS

In the first stage of work, a geometrical approach for recovering position of a point P_0 in 3D space with non-parallel image axis stereo pairs is presented instead of basic triangulation algorithm for stereo position recovery, which is valid only for parallel image axis camera setups.

The method proposed requires 3D transformations to obtain necessary point position vectors in appropriate coordinate frame and analytical calculations to get lines from points and then to find intersection point of two lines.

Key idea of derivations is that if camera center(O_L,O_R) and image point corresponding to real world object feature in any coordinate frame (base frame of robot manipulator in our case) are known for both cameras, then it is possible to find coordinates of points by intersecting lines from left camera points and right camera points.

3.1. Definitions: Coordinate Frames, Points, Mathematical Relations

To derive an algorithmic layout for operation, results from camera calibration process, physical parameters of setup and basic theoretical aspects of projective geometry are utilized.

Focal distance and orientations of image planes are results of camera calibration algorithm, which is through observation of checkerboard pattern from different positions and orientations.

Grid coordinate frame is the frame attached to calibration image (Checker Board) and denoted with subscript or superscript "G". Camera coordinate frame is the coordinate frame of the camera, which the grid is observed and denoted with subscript or superscript "C or L (for left camera) or R (for right camera)".

Coordinate frames of robotic system are respectively given as: $F_w(O_w)$: World coordinate frame. Origin (O_w) is at the projection of midpoint of drive axis to floor. Absolute motion coordinates are measured via this coordinate system. $F_c(O_c)$: Vehicle coordinate frame. Origin (O_c) is attached to midpoint of driven axis. $F_m(O_m)$: Manipulator coordinate frame. Robot motion is subject to the relative movements of target with respect to cart coordinate frame. Extrinsic parameters for camera coordinate frames are rotation (a 3x3 rotation matrix) and translation (a 3x1 vector) of camera reference frames in grid reference frames. Rotation matrices (R_G^L, R_G^R) consequently define the rotational transformation from grid reference frame to left and right camera reference frames, respectively.

3.2. Derivation of Equations

As mentioned while defining coordinate frames, it is necessary to know homogenous transformations to derive stereo vision algorithm. Exploited camera calibration routine generates homogenous transformations matrices from grid frame to left and right camera frames. By performing stereo calibration with these results, pose of right camera frame is also calculated. $R_G^L, R_G^R, (\vec{o}_{GL})_G, (\vec{o}_{GR})_G, (\vec{o}_{LR})_G, R_R^L$ are found by implementing procedure developed by Bouget [9].

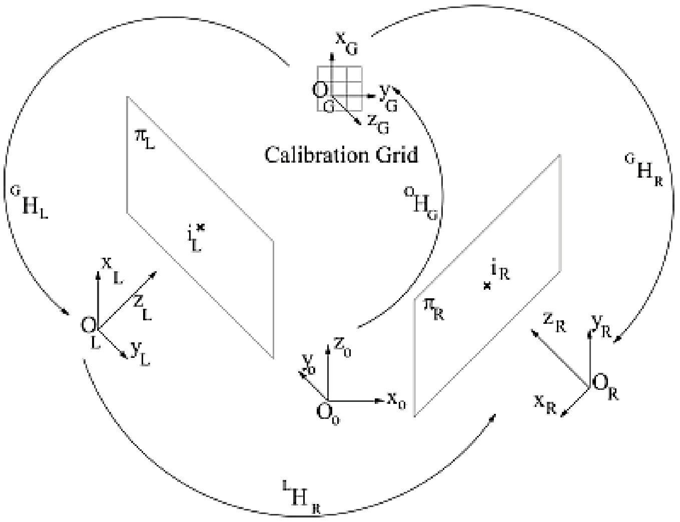

Fig. 5. Coordinate frames of vision system. (O_0 corresponds to origin of the manipulator O_m)

The triangulation algorithm is solved in left camera frame. The first points for line equations are:

$$\{\vec{o}_L\}_L = [0 \quad 0 \quad 0]^T \tag{15}$$

$$\{\vec{o}_R\}_L = \{\vec{o}_{LR}\} \tag{16}$$

To formulate a line, another point through which follows or an orientation vector is necessary. Focal distance in pixels is calculated in camera calibration algorithm. The z component of second point for line can be obtained from the knowledge of pinhole camera model, which states that center of the camera is on the normal of the image plane (aligned with Z axis of the camera) and at a distance of focal length. Other components are image coordinates of the projection of real point p onto left ant right image planes respectively.

$$\{\vec{p}_L\}_L = [j_L \quad i_L \quad f_L]^T \tag{17}$$

$$\{\vec{p}_R\}_R = [j_R \quad i_R \quad f_R]^T \tag{18}$$

$$\{\vec{p}_R\}_L = \{\vec{o}_R\}_L + R_R^L\{\vec{p}_R\}_R \tag{19}$$

Concerning next step in algorithm, which is finding the intersection point of two lines, it is necessary to point out the fact that intersection of 3D lines are highly sensitive to exact recovery of the points. This fact results mainly a least square solution in standard triangulation algorithm. To overcome this handicap, a projection of stereo setup onto xy plane is considered. Losing one dimension in calculations leads familiar planar equations.

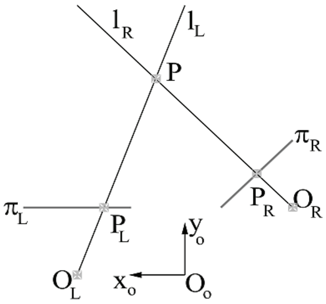

Fig. 6. Projection of stereo setup on to xy plane

Exploiting homogenous coordinates in calculations gives explicit equations for y and x of target point (**P**=[x y 1]^T). Known points O_L ,P_L ,O_R ,P_R , are converted to these representation and lines, intersecting at point P_0 , L_R ,L_L are found by cross product. And their intersection P_0 is also calculated via cross product of lines in homogenous form.

$$l_L = \{\vec{o}_L \times \vec{p}_L\}_{L,xy} \tag{20}$$

$$l_R = \{\vec{o}_R \times \vec{p}_R\}_{L,xy} \tag{21}$$

$$\{P\}_L = l_R \times l_L \tag{22}$$

Result gives two parametric explanation for x and y of the target point. To extract exact Cartesian coordinates z must be found via pinhole geometry with triangulation (disparity in y axis (height difference in images are utilized to determine actual height of target). Recalculating depth of point P. Using depth value recovered, position vector is then calculated in left camera frame using pinhole camera calculations. This approach extends the stereovision algorithm based on triangulation to the more general case by expanding field of common view in stereo system

For robotic applications, it is also necessary to find a relation between camera reference frame and robot base coordinate so that a relation between vision system and robotic system can be constructed. A straight forward method to find out this relationship is placing the grid in a proper pose with respect to robot base reference frame. This strictly defines homogenous transformation H_G^O.

Using camera calibration results and robot grid transformations following equations give positions of camera coordinate frame centers in robot base reference frame.

$$\{P\}_O = H_G^O \{P\}_G \tag{23}$$

When the target position is known, it is possible to solve inverse kinematic equations. But one special issue should also be considered when solving iteratively equation z. The increment of iteration is determined by the resolution of digital analogue converter. Using smaller or larger increment values leads quantization errors besides the error which is arisen from iterative calculation.

One issue which is also necessary to develop a constraint is how system selects a solution to implement from the set of all possible solutions. Considering reaction time of the robot system, optimal solution is set to be closest pose in configuration space.

4. EXPERIMENTAL RESULTS

In the experiments, a PC with 1.7 MHz Pentium microprocessor and USB web cams does the task of image acquisition and processing. The image processing time is associated with image size. We use a 640x480 image. The mobile manipulator (figure II), which the stereo setup is to be mounted, is developed and manufactured in Dokuz Eylul University Mechatronics Laboratory. Its structural properties are given in table 1.

Table 1. Link parameters for test evaluations

Length (in mm's)	Variable
No constant parameters	d_1, θ_1
l_2=344	θ_2
l_3=340	θ_3
l_4=110	θ_4

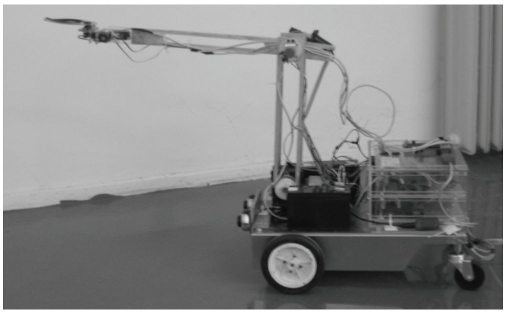

Fig. 7. Mobile manipulator

Two experimental evaluations are made to test the platform. In the first experiment, stereo setups with parallel image axis and in the second a system with non-parallel axis are tested. Extrinsic parameters of systems found from calibration are conveyed to algorithm as necessary initial data Afterwards presented algorithm is applied in following steps for both test setups: 1) The target is placed to the previously measured coordinates 2) The stereovision setup obtains visual information of the target and calculates 3D coordinates (Table 2 & Figure 8). 3) Using equations 13-15, Manipulator pose is calculated (Table 4).

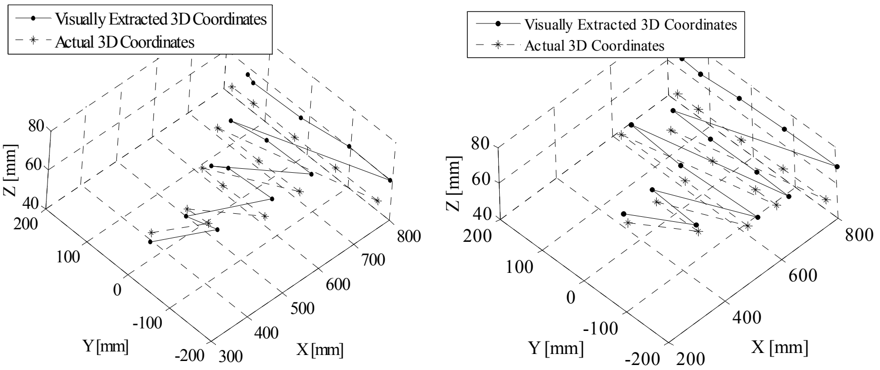

Fig. 8. Results of stereovision algorithm (a) from parallel axis (b) non-parallel axis setup

Table 2. Visually measured 3D coordinates and their actual values

(a) Parallel Axis Stereo Setup

X_A	Y_A	Z_A	X_M	Y_M	Z_M	|Error|
360	0	55	369	8	47	14
460	-50	55	463	-71	55	21
660	100	55	687	-102	61	28
760	150	55	789	138	59	32

(b) Non-parallel Axis Stereo Setup

X_A	Y_A	Z_A	X_M	Y_M	Z_M	|Error|
460	-100	55	461	-93	57	7
560	0	55	569	15	59	18
660	100	55	681	108	61	24

For a target that is between 0.3 and 0.7 meter away, the maximum position error of distance estimation error is less than 0.04 meter and error in position calculations are about 0.01 meter. That result satisfies expectation of 3D recovery within workspace of the manipulator mounted on cart.

Because of the fact that θ_2, θ_3 are same for every equal z, this method decouples tracking task in z axis from positioning task in xy axis as another consequence main tracking task is reduced to differential drive control problem.

5. DEMONSTRATIVE TASK

To enlighten dynamical characteristics of operation of mobile manipulator, a sequential control task is designed. An important issue remained not solved is how to control position of cart as it is described in the previous section, only velocity equations are available. To solve this problem vision setup is implemented. Target-planar manipulator alignment is satisfied by control of deviation from the image center of the left camera which is placed so properly that its center line is corresponding to operation plane of the manipulator. Approach of the cart to target is controlled via stereo system output.

With most basic motion planning routine, the differential drive can move between any two configurations by:

- First rotating it to point the wheels to the goal position, which causes no translation.
- Translation through target.
- Rotation to the desired orientation, this again causes no translation.
- Stereo algorithm result to find relative target position
- Solve inverse kinematics and execute manipulator motion

In the following, results of the described task are given.

Table 3. Calculated references through algorithm

References in task space		References in joint space	
X [mm]	776	d1 [mm]	476
Y [mm]	476	θ_1 [deg]	27.29
Z [mm]	86	θ_2 [deg]	72.48
		θ_3 [deg]	105.58

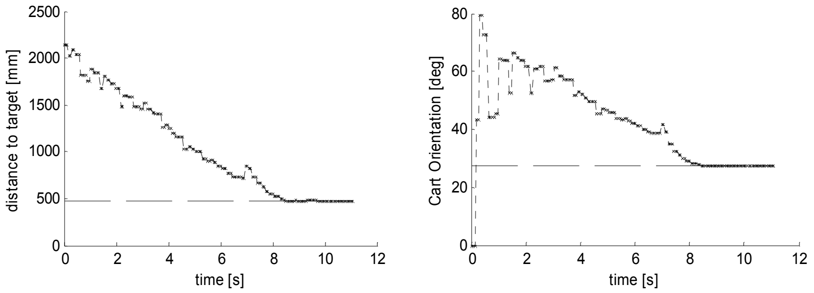

Fig. 9. Mobile platform response to references (-- reference -x- actual)

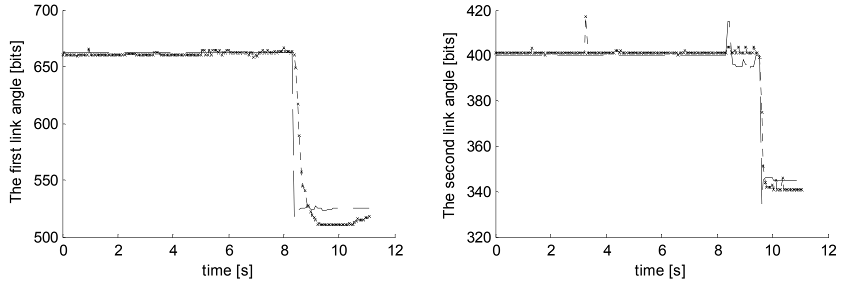

Fig. 10. Manipulator response to references (-- reference -x- actual)

6. CONCLUSION

In this paper, a stereovision based algorithm for generating position references for a mobile manipulator is introduced. Algorithm realized sequential application of functions based on image processing projective geometry and kinematical analysis. The results demonstrate that in the intersection of field of view of the cameras position recovery can be accomplished with an error of 0.044 m (combined error for both stereo vision algorithm and manipulator reference calculations).

REFERENCES

1. Khatib, O., Yokoi, K. Chang, K., Ruspini, D., Holmberg R. & Casal,A. "Coordination and Decentralized Cooperation of Multiple Mobile Manipulator". Journal of Robotic Systems vol 13(11), pp. 755-764, 1996
2. Campion, G., Bastin, G. & Andrea-Novel, B. "The vector field histogram fast obstacle avoidance for mobile robots". IEEE Transactions on Robotics and Automation, vol. 12(1), pp.47-62, 1996.
3. Jörg, K.W. "World modeling for an autonomous mobile robot using heterogenous sensor information". Robotics and Autonomous. Systems., vol.14, pp. 159-170, 1995
4. Laumond J.P.(Ed.) Robot motion planning and control. Berlin:Springer, 1998
5. Bloch, A., Baillieul, J., Crouch, P.E. & Marsden, J.E. Nonholonomic mechanics and control. Berlin: Springer, 2003.
6. Lambrinos, D., Moller, R., Labhart, T., Pfiefer, R. & Wehner., R. A mobile robot employing insect strategies for navigation. Robotics and Autonomous. Systems., 30, 39-64,2000.
7. Fu, K.S., Gonzalez, J. & Lee, S. Robotics: Control, sensing, vision, and intelligence. New York: McGraw-Hill, 1987.
8. Hootsmans, N.A.M., & Dubowsky, S. The control of mobile manipulators including vehicle dynamic characteristics, In Proceedings of. IV Topical Meeting on Robotics and Remote Systems, 24-28, NM Albuquerque, 1991.
9. Bouguet J.Y. (2000), Camera Calibration Toolbox, http://www.vision.caltech.edu/bouguetj/.

KORIŠĆENJE DURBINSKE STEREOVIZIJE ZA PROCENU POKRETLJIVOSTI REFERENCE ZA MOBILNI MANIPULATOR

Levent Çetin, Erol Uyar

Ovaj rad se bavi projektovanjem i primenom stereo odrednice koja se postavlja na mobilni manipulator. Ova postavka se koristi za dobijanje referentnih tačaka mobilnog manipulatora dinamički. Zadaci, 3D povraćaj i izvlačenje karakteristika postižu se u kamera- referentnom okviru a onda se transformišu u robotski koordinantni okvir. Povraćaj pozicije podataka konvertuje se u položaj manipulatora dvofaznim algoritmom: iterativan pristup za pozicioniranje i inverzna kinematika proračuna za orijentaciju zahteva. Kompjuterska primena ovog algoritma razvija se i testira za upravljanje pozicijom mobilnih manipulatora sa aktivnom vizijom.

Ključne reči: *Stereo Vizija, Inverzna kinematika, Mobilni manipulator*