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IMAGE BASED VISUAL SERVOING OF A NON-HOLONOMIC MOBILE PLATFORM USING A PAN-TILT-HEAD

BERND AUGUSTIN, THORSTEN LIETMANN, BORIS LOHMANN

Institute of Automation (IAT), University of Bremen, Otto-Hahn-Allee NW1,
28359 Bremen, Germany, {augustin, lietmann, bl}@iat.uni-bremen.de

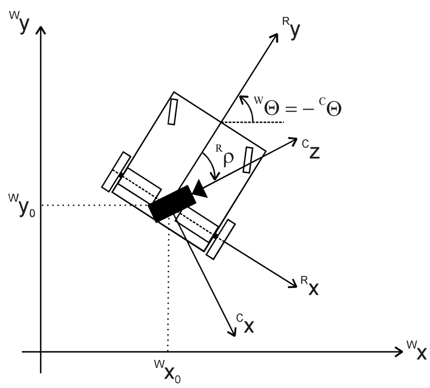
Abstract. In this paper a visual controller based on the image-jacobian-matrix is proposed and used to navigate a mobile platform with the help of landmarks. Due to the non-holonomic constraints of our mobile platform the image based visual servoing has to be supported by an additional trajectory tracking control. While the platform moves the visual controller continuously calculates more precise goal-poses for the platform. The additional trajectory tracking ensures that the mobile platform is guided on a resulting trajectory into its desired goal-pose. Furthermore, a pan-tilt-head is used for turning the camera and keeping the landmark in the camera's field of view (feature tracking). This new method is tested with the real system and the results are shown in this paper.

Key Words. Mobile Robots, Autonomous Navigation, Visual Servoing.

1 INTRODUCTION

A typical approach to autonomous mobile robot navigation is to estimate the position and orientation by using wheel rotation information (odometry) with the help of a map of the work space. Because of wheel slipping there is a failure in calculating the pose of the mobile platform which is growing with the distance covered. For this reason and to navigate in unknown environments additional external sensors are used. In our scenario the mobile robot is equipped with a CCD-camera mounted on a pan-tilt-head. By using image based visual servoing it is no longer necessary to calculate the absolute pose of the mobile robot. Navigation of the robot is based only on the data of the camera image which makes it possible to get the robot into a pose relative to an object in the work space. However, navigating a non-holonomic mobile robot causes the problem that the number of states is greater than the number of control inputs. Because of this property of our mobile robot (wheelchair, fig. 1a) it is not possible to apply known approaches of image based visual servoing directly [1]. A similar formulation of this problem is solved in [2] by following a trajectory of features in the camera's image. Additional movement of the camera is achieved in [3] by fixing it on a manipulator. An approach to navigate a vehicle without using the image-jacobian-matrix is shown in [4] where the vehicle is steered by its front wheels.

a)



b)

Fig. 1: a) The real system
b) Wheelchair-camera-configuration (top view)

This paper presents a new method of navigating a non-holonomic mobile platform. The approach of image based visual servoing, originally proposed for the control of manipulators, is extended and an additional trajectory tracking is used to control the movement of the wheelchair. This trajectory tracking enables the wheelchair to move from its start-pose on a smooth course to a desired goal-pose. First the desired goal-pose for the mobile robot is calculated by image based visual servoing. Then the additional trajectory generation plans and controls (tracks) the movement that the platform has to execute (drive controller). While the platform is moving its desired pose is continuously updated by the visual controller. The trajectory generation corrects the previous trajectory to the new desired pose and the controller guides the platform to the new trajectory. Furthermore, a feature tracking controller is introduced to keep the landmark in the camera's field of view during wheelchair motion.

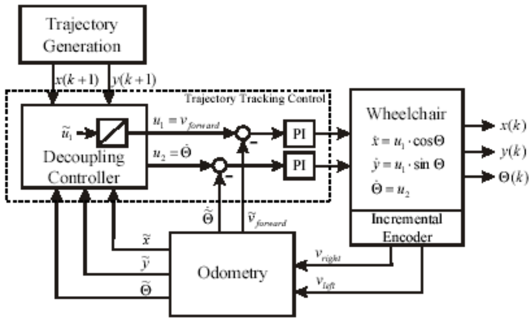
2 MOBILE PLATFORM AND DRIVE CONTROLLER

Our mobile platform (a motorized electric wheelchair) is a non-holonomic mechanical system because it is not possible to move in the direction of the axis of its rear wheels. The problem to be solved is to guide the wheelchair into a desired pose relative to an object (docking-procedure) based on information from the camera image. This desired pose in the camera image has to be teached before starting the control process (teaching by showing, [5]). The wheelchair is equipped with two independently driven rear wheels and two non-driven supplementary front wheels. The two electric motors of the rear wheels are controlled in a way that the forward velocity u_1 and the angular velocity u_2 of the wheelchair can be considered as the *control input variables* of the system. The non-holonomic kinematics of our autonomous mobile wheelchair are represented by (1):

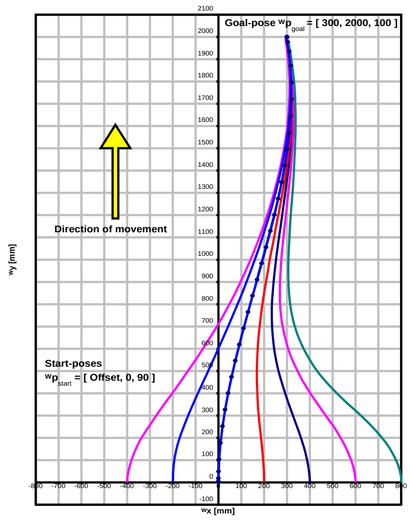
$$\begin{aligned} {}^W\dot{x} &= u_1 \cdot \cos\left({}^W\theta\right) \\ {}^W\dot{y} &= u_1 \cdot \sin\left({}^W\theta\right) \\ {}^W\dot{\theta} &= u_2 \end{aligned} \tag{1}$$

The state vector of the wheelchair ${}^W\underline{\mathrm{p}} = [{}^W\mathrm{x},\ {}^W\mathrm{y},\ {}^W\theta]^T$ consists of the two cartesian coordinates in the driving plane ^{W}x and ^{W}y and the turn angle ${}^W\theta$. This turn angle corresponds to the angle between the driving direction of the wheelchair and the x-axis of the world coordinate frame, compare fig. 1b).

Due to the constraints of the wheelchair the visual controller has to be supported by an additional trajectory tracking control [6]. Trajectories with a smooth course between the start- and goal-pose are generated which can be driven by the wheelchair (block "trajectory generation" in fig. 2a). The trajectories are calculated in a way that the wheelchair not only reaches its desired goal coordinates ${}^W\mathrm{x}_d$ and ${}^W\mathrm{y}_d$ but also its desired goal angle ${}^W\theta_d$. A trajectory tracking control system has been implemented which keeps the wheelchair on the given trajectory [6]. From the positions and velocities of the driven wheels, measured with the help of digital encoders installed on the wheel shafts, the actual pose of the wheelchair is calculated continuously (block "odometry"). From this and from the desired trajectory, a *decoupling state-feedback controller* generates appropriate control input signals u_1 and u_2, compare (1). Within two underlying control loops, additional PI-compensators improve the dynamic and steady-state behaviour of the velocities u_1 and u_2. The trajectory tracking control ensures that initial errors and deviations from the prescribed trajectory are compensated. Fig. 2b) shows how the wheelchair is driven onto the desired trajectory (dotted line, starting in ^{W}x = ^{W}y = 0 mm) starting from different initial error poses [6].



a)



b)

Fig. 2: a) Drive controller (trajectory generation and trajectory tracking control)
b) Movement of the wheelchair onto a desired trajectory (with and without error in its start-pose)

3 IMAGE BASED VISUAL SERVOING

Image based visual servoing describes the general task of moving a robot by visual informations delivered from a camera [7]. Therefore, in a closed loop control algorithm images are continuously recorded and the robot is moved on the basis of the gained image information. This process continues until the desired task is fulfilled. Intention of the control algorithm is to move the wheelchair into a suitable pose relative to an object on the basis of visual information from the camera. To accomplish this, usable features for the control algorithm are evaluated from the camera image by image processing. These features are the centre point coordinates of four blobs (landmark, see fig. 3) which are extracted from the image by a blob-analysis. These centre point coordinates are stored in the sensor coordinate frame {S} which is related to the camera's CCD-chip. Equation (2) shows the feature-vector (for one blob) which is a function of the camera-pose ${}^{C}\underline{\mathrm{p}}$. For each blob the feature-vector increases by two rows.

$$ {}^{S}\underline{x} = {}^{S}\,\underline{x}\left({}^{C}\underline{p}\right) = \begin{bmatrix} {}^{S}x \\ {}^{S}y \end{bmatrix} \tag{2} $$

By differentiating this equation a relation between the time-derivatives of image-feature-vector and velocity-vector of the camera can be obtained (3):

$$ {}^{S}\underline{\dot{x}} = J\left({}^{S}p\right) \cdot {}^{C}\underline{\dot{p}} \tag{3} $$

The matrix J(${}^{C}\underline{\mathrm{p}}$) is an image-jacobian-matrix, relating the rate of change in camera-pose to the rate of change in feature space (4):

$$ J\left({}^{C}\underline{p}\right) = \frac{\partial\, {}^{S}\underline{x}}{\partial\, {}^{C}\underline{p}} \tag{4} $$

Using the approximate solution (7) of equation (3) and by comparison of actual and desired features (see fig. 3) the controller calculates the modification of the camera pose. This new camera pose (camera coordinate frame) can be converted into a new wheelchair pose (world coordinate frame) by coordinate transformation [8].

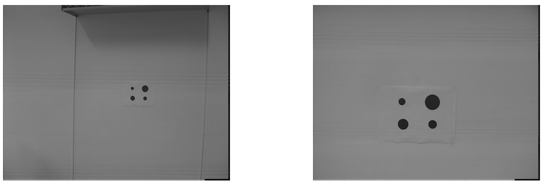


Fig. 3: Camera image in start-pose (left) and in goal-pose (right)

The desired features ${}^{S}\mathrm{x}_{d}$ in the goal-pose have to be defined before starting the control algorithm which is done by "showing". Therefore, the wheelchair is driven to its goal-pose (e. g. a pose relative to a table), the corresponding image is recorded, the features are extracted and saved as desired features. While the visual controller is working and the wheelchair is driving the actual image features are moving into the desired image features. After this is done the wheelchair is in the same relative pose to the landmarks as in the teaching process and the docking-procedure is fulfilled.

In order to calculate the motion of the camera, the controller has to generate movements in the three dimensional camera coordinate frame {C} from the control error in the two dimensional sensor coordinate frame {S}. This transformation is done with help of the image-jacobian-matrix J, as introduced in (3) and shown in detail in (5). This matrix J expresses a linear transformation of a modification of the camera pose ${}^{C}\underline{\dot{\mathrm{p}}}$ (cause), described in camera coordinates, into a corresponding modification of the projection of a rigid point or blob ${}^{S}\underline{\dot{\mathrm{x}}}$ (effect), described in sensor coordinates.

$$ \underbrace{\begin{bmatrix} {}^{S}\dot{x} \\ {}^{S}\dot{y} \end{bmatrix}}_{{}^{S}\underline{\dot{x}}} = \underbrace{\begin{bmatrix} -\frac{f}{{}^{C}z} & 0 & \frac{{}^{S}x}{{}^{C}z} & \frac{{}^{S}x\,{}^{S}y}{f} & -\frac{f^2+{}^{S}x^2}{f} & {}^{S}y \\ 0 & -\frac{f}{{}^{C}z} & \frac{{}^{S}y}{{}^{C}z} & \frac{f^2+{}^{S}y^2}{f} & -\frac{{}^{S}x\,{}^{S}y}{f} & -{}^{S}x \end{bmatrix}}_{J} \cdot \underbrace{\begin{bmatrix} t_x \\ t_y \\ t_z \\ \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}}_{{}^{C}\underline{\dot{p}}} \tag{5} $$

Equation (5) shows the connections for one blob (two features) and a possible motion of the camera in six degrees of freedom (where t_i represents the translational and ω_i the rotational velocities). For each blob the image-jacobian-matrix increases by two rows. If the camera is not moved in all six degrees of freedom the corresponding columns in the image-jacobian-matrix vanish. If the camera is mounted on the wheelchair it has the following three degrees of freedom (compare fig. 1b):

$$ t_x = {}^{C}\dot{x}, \quad t_z = {}^{C}\dot{z}, \quad \omega_y = {}^{C}\dot{\theta} \tag{6} $$

3.1 Control Law

To be robust against noise of measurement, the number of image features should be chosen greater than the number of degrees of freedom. For navigating the wheelchair, eight features (four blobs) are used. In this case, (5) results in the following approximation for the desired vector ${}^{C}\underline{\dot{p}}$ by establishing the pseudo inverse J^{+}:

$$ {}^{C}\underline{\dot{p}} = J^{+} \cdot {}^{S}\underline{\dot{x}} \tag{7} $$

The elements of the controller input vector ${}^{C}\underline{\dot{p}}$ and of the feature-vector ${}^{S}\underline{\dot{x}}$ in (7) are velocities. Considering we have to implement a discrete time controller (see fig. 4) we obtain a discrete controller input from (7) utilizing a sampling time T_s. Then the task is defined as the regulation of an error function to zero. The system error is rewritten as:

$$ \underline{e} = \Delta\, {}^{S}\underline{x} = {}^{S}\,\underline{x} - {}^{S}\underline{x}_d \tag{8} $$

A suitable behaviour of the error $\underline{e}$(t) is described by the first order differential equation (9):

$$\dot{\underline{e}} = -K_f \cdot \underline{e} \tag{9}$$

With a suitable choice of the (diagonal) matrix K_f an exponential convergence of the error term to zero while t$\rightarrow \infty$ is ensured, provided that the corresponding required control input signals can be generated. By substituting (8) into (9) and substituting the result into (7), we obtain the following feedback control law in a discrete-time formulation:

$$\Delta\,{}^{C}\underline{p} = -J^{+} \cdot K_f \cdot T_s \cdot \Delta\,{}^{S}\underline{x} \tag{10}$$

A stability analysis of the control law (10) can be found in [9]. The resulting control scheme is shown in fig. 4 where the block "visual controller" includes the control law (10). The visual controller calculates a step of movement in the three coordinates $\Delta^{W}x, \Delta^{W}y, \Delta^{W}\theta$. Based on these, the block "drive controller" generates an appropriate trajectory and controls the movement of the wheelchair along this trajectory.

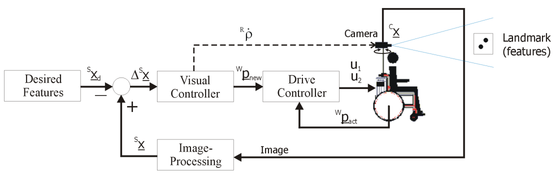


Fig. 4: Image based visual servoing of the wheelchair

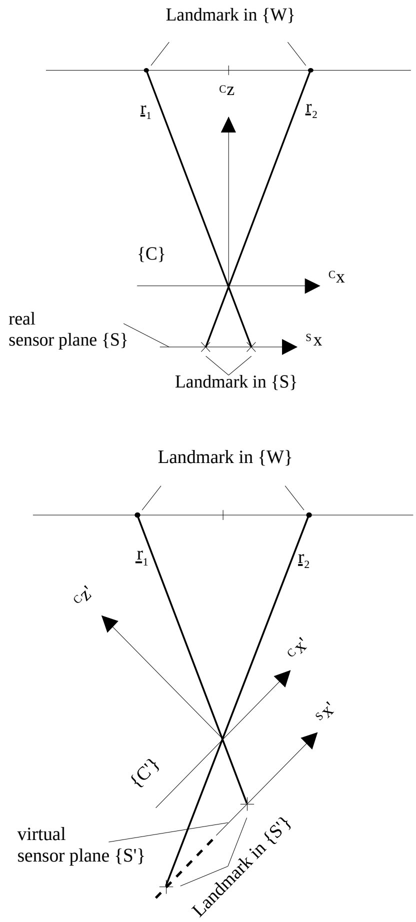
3.2 Feature Tracking

For the realisation of image based visual servoing it is required that the visual features (blobs) stay in the camera image during the whole control process. If the camera is fixed rigidly on the wheelchair this results in a small work space for the docking-procedure. To overcome this problem the camera is mounted on a pan-tilt-head. So, an independent feature tracking control algorithm (included in the block "visual controller") actuates the pan-angle and keeps the features in the camera's field of view. This is done by evaluation of the coordinates of the blobs on the sensor plane $\{S\}$ and generation of an appropriate control input for the pan-tilt-head to keep the blobs in the middle of the camera image.

Caused by the feature tracking a difference angle ${}^{R}\rho$ between the orientations of camera and wheelchair arises (compare fig. 1b). This angle is not considered in the control law (10). So, the image based visual servoing assumes that camera and wheelchair always point in the same direction. To maintain the common image based visual servoing statements made above a new method is introduced in this paper using a so called *virtual sensor plane* (fig. 5).

In fig. 5a) the camera coordinate system $\{C\}$ is shown if the landmark is in the middle of the camera image (pinhole camera model). It is assumed that in this case camera and wheelchair do *not* point in the same direction. Now, the camera system $\{C\}$ is transformed by coordinate transformation into the camera system $\{C'\}$ as it is shown in fig. 5b). This can be done because the difference angle ${}^{R}\rho$ is known. The new camera system $\{C'\}$ points in the same direction as the wheelchair. By the equations of the pinhole camera model the visual features can be calculated as they would appear on the rotated sensor plane $\{S'\}$. The resulting feature coordinates could not be located on the real sensor plane (the CCD-chip), but may be located on a *virtual sensor plane* which dimensions are theoretical infinite.

platform Using this virtual sensor plane the above described image based visual servoing can be applied without any modifications. The difference angle between camera and wheelchair caused by the feature tracking is considered by transformation of the features onto the virtual sensor plane.



a)

b)

Fig. 5: a) original system (top view)
b) rotated system (virtual sensor plane)

4 EXPERIMENT

The trajectories which are generated during wheelchair motion are not planned from the wheelchairs actual-pose but from its original start-pose (the start-pose at the beginning of the docking-procedure). Therefore the elements of K_f in (10) are chosen large enough to calculate goal-poses which are near to the exact desired-pose (in camera coordinates). Because the start-pose is relatively far away from the exact goal-pose the goal-pose calculated in the first step is relatively inaccurate. So, continuously new pictures are taken while the wheelchair is moving and continuously new goal-poses are calculated. The nearer the wheelchair gets to the real goal-pose the better the visual controller is able to calculate the exact goal-pose, provided that the image-features are delivered by the camera exactly. The generation of trajectories always beginning in the original start-pose is possible by using the odometry data and a coordinate transformation [8].

With this solution it is possible to repeatedly calculate new trajectories from the original start-pose of the wheelchair into the new goal-poses generated by image based visual servoing. So, a set of trajectories is produced between the start-pose and a lot of goal-poses which are calculated by the visual controller during wheelchair motion (see fig. 6). During wheelchair motion the desired positions of the actual trajectory section are forwarded to the trajectory tracking control which keeps the wheelchair on the momentary trajectory. If a new goal-pose is calculated and a new trajectory is generated the actual trajectory is updated. The trajectory tracking control guides the wheelchair to the updated trajectory in the same way as it is shown in fig. 2b). During this procedure all momentary actual trajectory sections are joined together and yield to a resulting trajectory which can be driven by the wheelchair.

In the experiment shown in fig. 6 the wheelchair reached its goal-pose with an error of ${}^{W}\underline{\mathrm{p}} = [10\,\mathrm{mm}, 38\,\mathrm{mm}, 2\,°]^T$. The turn angle is not plotted in this figure, because it arises automatically from the course ${}^{W}\mathrm{x}(t)$ and ${}^{W}\mathrm{y}(t)$ of the calculated trajectories. The start-pose of the wheelchair was at ${}^{W}\underline{\mathrm{p}}_{start} = [0\,\mathrm{mm}, 0\,\mathrm{mm}, 90\,°]^T$.

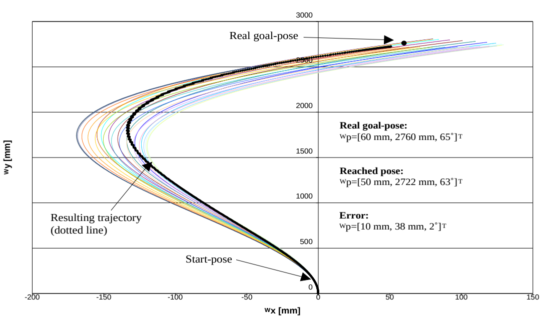


Fig. 6: Set of trajectories and resulting trajectory

5 CONCLUSION

This paper has presented how the task of a docking-procedure of a mobile platform can be solved based on image based visual servoing using a camera mounted on a pan-tilt-head. The control algorithm is able to guide the wheelchair into its desired goal-pose on the basis of image informations delivered by a camera. A corresponding discrete time control scheme which uses the image-jacobian-matrix was presented. By usage of an additional trajectory generation the visual controller represents a suitable solution to navigate a mobile platform. In order to achieve a smooth and driveable trajectory repeatedly new trajectories are generated during wheelchair motion from the original start-pose into the new calculated goal-poses. Out of this group of trajectories a resulting trajectory arises which guides the wheelchair into the goal-pose. The introduced feature tracking ensures that the landmark is kept in the camera's image during movement of the wheelchair and thus enlarges the work space of the wheelchair.

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