

# Camera Calibration for Reliable Object Manipulation in Care-Providing Robot FRIEND

Torsten Heyer, Sorin M. Grigorescu, Axel Gräser

Institute of Automation (IAT), University of Bremen  
Otto-Hahn-Allee 1, 28359 Bremen, Germany  
{theyer, grigorescu, ag}@iat.uni-bremen.de

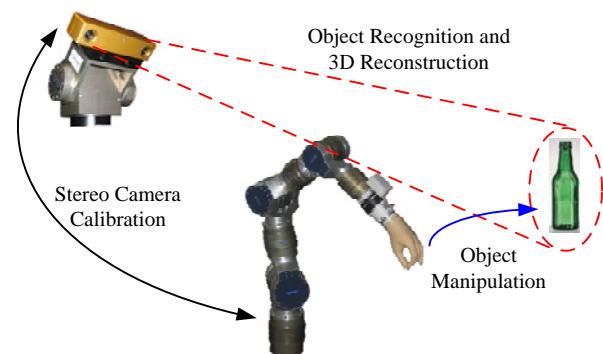
## Abstract

In this paper the on-line calibration method of the care-providing robotic system FRIEND is discussed. The objective of the calibration concept is to maintain the coordinate transformations within the system up-to-date with respect to external influences for the purpose of reliable object grasping and manipulation. One of these influences, present during robotic operation, is the shattering phenomenon introduced in the design of the robotic platform, that is in the interconnections between the major components of the robot. In this work, a vision-based calibration method for coping with external influences is used for on-line updating of the necessary coordinate transformations. The performance of the calibration method is evaluated through experimental results.

## 1 Introduction

Accurate camera calibration is a key requirement for object recognition in robot vision systems which have to extract reliable 3D visual information regarding the surrounding environment. The process of camera calibration is basically represented by finding those quantities that affect the imaging process, that is the camera's position and orientation (pose), described by the *extrinsic camera parameters* and the camera's internal calibration parameters (e.g. focal length and lens distortion) also known as *intrinsic parameters*. The objective of the calibration procedure is to calculate the camera's projection matrix, composed of both extrinsic and intrinsic parameters, which describes the mapping of the camera from 3D world points to 2D points in an image. Using this matrix, derived from the camera's geometry, 3D poses of objects present in the field of view of the camera system can be reconstructed in a virtual world model of a robot for the purpose of 3D environment understanding. In **Figure 1** an example of object recognition for the purpose of grasping and manipulation, where calibration of the camera system is crucial, is given. In order for the manipulator arm to grasp the object of interest the pose of the camera with respect to a fixed coordinate system, in this case the robot's base joint, commonly referred to as the *world coordinate system*, needs to be known in order to extract visual information from the environment, which can be used for manipulator control. The

precision of this transformation directly influences the reliability of object manipulation since the pose of the object, determined from acquired images, is calculated with respect to the world coordinate system.



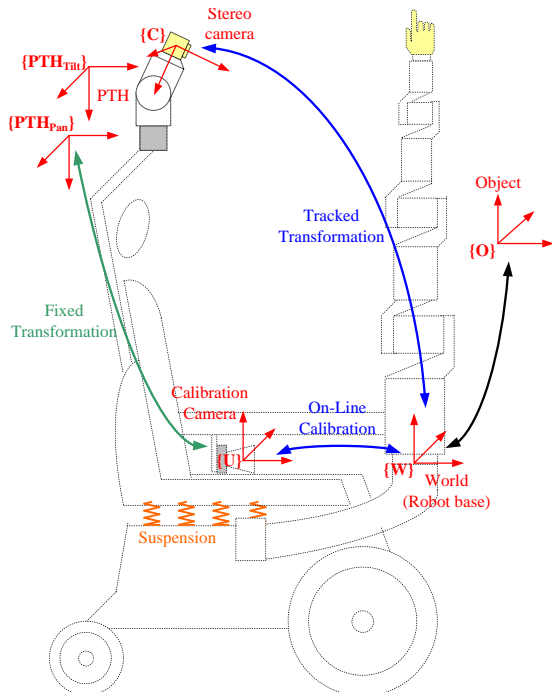
**Figure 1:** Object recognition for object grasping and manipulation.

Such a robot, where camera calibration plays a central part, is the care-providing robotic system FRIEND (*Functional Robot arm with friENdly interface for Disabled people*) shown in **Figure 2**. FRIEND is a semi-autonomous robot designed to support disabled and elderly people in their daily life activities, like preparing and serving a meal, or reintegration in professional life e.g., at a library desk or in a workshop. The robot is the third



**Figure 2:** The care-providing robotic system FRIEND.

generation of such robots developed at the Institute of Automation of University Bremen within different research projects [6]. It is equipped with a 7 Degrees of Freedom (DoF) manipulator arm mounted on an electrical wheelchair and a series of sensors used by the robot to understand the environment. One of these sensors is a Bumblebee<sup>®</sup> stereo camera attached to a 2-DoF Pan-Tilt Head (PTH) unit mounted on a rack behind the user. The camera is used to acquire visual information from the surrounding environment.



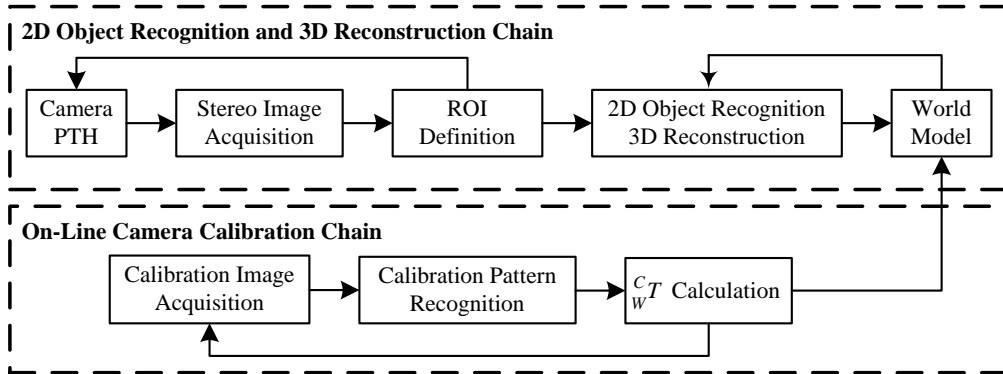
**Figure 3:** Structure and coordinate transformation in the robotic system FRIEND.

The FRIEND platform is a Meyra<sup>®</sup> electrical

wheelchair series 1.595 "NEMO" which mainly consists of two large components connected together: a basis on which the wheels and the manipulator arm are fixed and the seat for the user. The global stereo camera system which controls the robot is attached to the seat. The two parts are connected together by a set of spring suspensions, as depicted in **Figure 3**. The major problem in this configuration is that the pose of the global camera varies considerably with respect to the world coordinate system, taken as the manipulator's first joint, due to the suspension so that without any additional effort no reliable object manipulation is possible. This motion occurs e.g., when the wheelchair or the user in the seat are moving. Similar situation may occur in many service robot systems. The main goal of the work presented in this paper is to cope with this relative motion that constantly influences the pose of the global camera. For reliable object grasping in the FRIEND system an accuracy of 5-10mm for the calculated 3D pose is necessary. Due to the suspension this accuracy is not given and permanent calibration is necessary.

In literature, robotic systems that avoid the use of camera calibration are found [8, 13, 9]. This is the case of image based visual servoing, where image features are used directly to control the manipulator arm. Having in mind the complexity of the FRIEND system and the uncertainty of the scenes in which it operates, as depicted in Figure 2, a 3D virtual reconstructed environment was needed for the purpose of collision free manipulator path planning and object grasping. This could only be achieved through a calibrated camera system.

The large interest on autonomous robots encountered in the last decades also influenced the research on calibrating such systems. A number of robotic platforms involve external mechanical apparatus for calibration, like e.g. acoustic sensors [19] or coordinate



**Figure 4:** Block diagram of the FRIEND vision system with on-line camera calibration support.

measuring machines that estimate the manipulator’s end-effector pose mechanically [3]. The disadvantages of such configurations are price and requirement of special trained personnel that have to operate the measuring devices. A different class of robotic calibration methods are the vision-based ones which involve cameras and visual patterns. An extensive survey on vision-based calibration algorithms is given in [17]. The calibration parameters, that is extrinsic and intrinsic parameters, are calculated either using special visual patterns, or markers (e.g. known object points arrays) [14, 18], either using marker-free algorithms [2, 10]. For the case of robotic manipulators with an eye-in-hand camera, usually the robot arm is moved at a special predefined kinematic configuration where a calibration marker can be detected [7, 15].

In this paper a visual pattern based calibration concept for the FRIEND robotic system is presented. The paper is organized as follows. First, the transformation of coordinates within FRIEND is given in Section 2. The camera calibration technique used for coping with the disturbance introduced by suspensions is presented in Section 3. In Section 4 performance evaluation of the proposed calibration concept is given through experimental results. Finally, conclusions and outlook are presented in Section 5.

## 2 Coordinate transformations

In Figure 3 the transformation of coordinates within the FRIEND robotic system are displayed. In the following a transformation between two coordinate systems  $\{A\}$  and  $\{B\}$  is referred to as  ${}^A_B T$  (transformation of the coordinate system  $\{B\}$  with respect to  $\{A\}$ ). The objective of the vision system is to reliably determine the pose of the object of interest  $\{O\}$  with respect to the world coordinate

system of FRIEND  $\{W\}$ . The pose  ${}^O_W T$  of the object is determined via images acquired from the stereo camera  $\{C\}$  for which the transformation  ${}^C_W T$  is required. The orientation of  $\{C\}$  is controlled by changing the angles of the 2-DoF PTH module, that is modifying the pitch of the coordinate system  $\{PTH_{Pan}\}$  and the yaw of  $\{PTH_{Tilt}\}$ .

The calibration of the camera  $\{C\}$  with respect to the world coordinate system, namely the calculation of transformation  ${}^C_W T$ , is performed through the calibration camera  $\{U\}$ . As explained in introduction, the basic problem with calibrating the FRIEND robot is the suspension system between the two major components: the basis and the seat. This suspension introduces a shattering of the seat, and consequently of the stereo camera system  $\{C\}$  with respect to the world coordinate system  $\{W\}$ . If the transformation  ${}^C_W T$  is not correctly determined then the pose of the object  $\{O\}$  will be erroneously calculated and thus visual guided object grasping will fail. In order to cope with this problem the world coordinate system  $\{W\}$ , fixed on the basis of the platform, is tracked using the calibration camera  $\{U\}$  mounted at the seat with a fixed transformation with respect to pan-tilt-head unit base. By on-line determining the pose of  $\{U\}$  the final world to stereo camera transformation can be calculated as:

$${}^C_W T = {}^C_{PTH_{Tilt}} T \cdot {}^{PTH_{Tilt}}_{PTH_{Pan}} T \cdot {}^{PTH_{Pan}}_U T \cdot {}^U_W T. \quad (1)$$

Hereby the transformation  ${}^{PTH_{Pan}}_C T$  between the calibration camera and the pan-tilt-head unit base is fixed and have to be calculated only once. This is done with an external calibration application. The transformations  ${}^C_{PTH_{Tilt}} T$  and  ${}^{PTH_{Tilt}}_{PTH_{Pan}} T$  depend on the current angles for pan and tilt and are recalculated after every pan-tilt head movement. Since only the transformation  ${}^U_W T$  needs to be calculated in real-

time, the other ones are fixed for constant angles for pan and tilt and measurable, the above relation can be simplified as:

$$\frac{C}{W}T = \frac{C}{U}T \cdot \frac{U}{W}T. \quad (2)$$

In the following the concept and flow of information for calibrating the FRIEND robotic system will be explained.

### 3 Vision-Based Calibration in System FRIEND

The objective of the calibration concept within the robotic system FRIEND is to provide reliable pose estimation of the global stereo camera for the purpose of 3D object reconstruction and manipulator control. In **Figure 4** a block diagram representing the overall vision system of FRIEND, described in [4], is shown. On the upper part of the diagram the 2D object recognition and 3D reconstruction chain is represented. The 2D object recognition methods are applied on a calculated image Region of Interest (ROI) adapted for the imaged scene [4]. Depending on the properties of the ROI, the orientation of the global stereo camera is changed by modifying the angles of the PTH unit. For final 3D object reconstruction, information regarding the pose of the global camera is necessary. This information is stored in a 3D virtual environment, called *world model* which is further used by the 7-DoF manipulator arm for collision-free path planning and object grasping [16].

The pose of the global stereo camera is constantly monitored by the on-line camera calibration chain based on the calibration camera  $\{U\}$ . This is achieved by continuously calculating the transformation matrix  $\frac{C}{W}T$  using Equation 2. The calibration camera uses a calibration pattern mounted at the world coordinate system  $\{W\}$  and measures continuously the camera pose with respect to the world coordinate system. The tracking is performed using the ARToolKit (*Augmented Reality ToolKit*) library [11] which provides as output the pose of the camera with respect to the calibration pattern. The tracking accuracy is sufficient since the size of the pattern in image and the calibration camera resolution (1280x1024px) are high [12, 1]. The distance from camera to the pattern is approx. 300mm. As it will be explained in the performance evaluation section, the tests results indicated an accuracy of approx.  $0.5^\circ$  for orientation and less than 17mm for the estimated global camera position. These results are in accordance to the experimental results presented in [1], where a specific distribution of tracking accuracy for an ARToolKit pattern is given

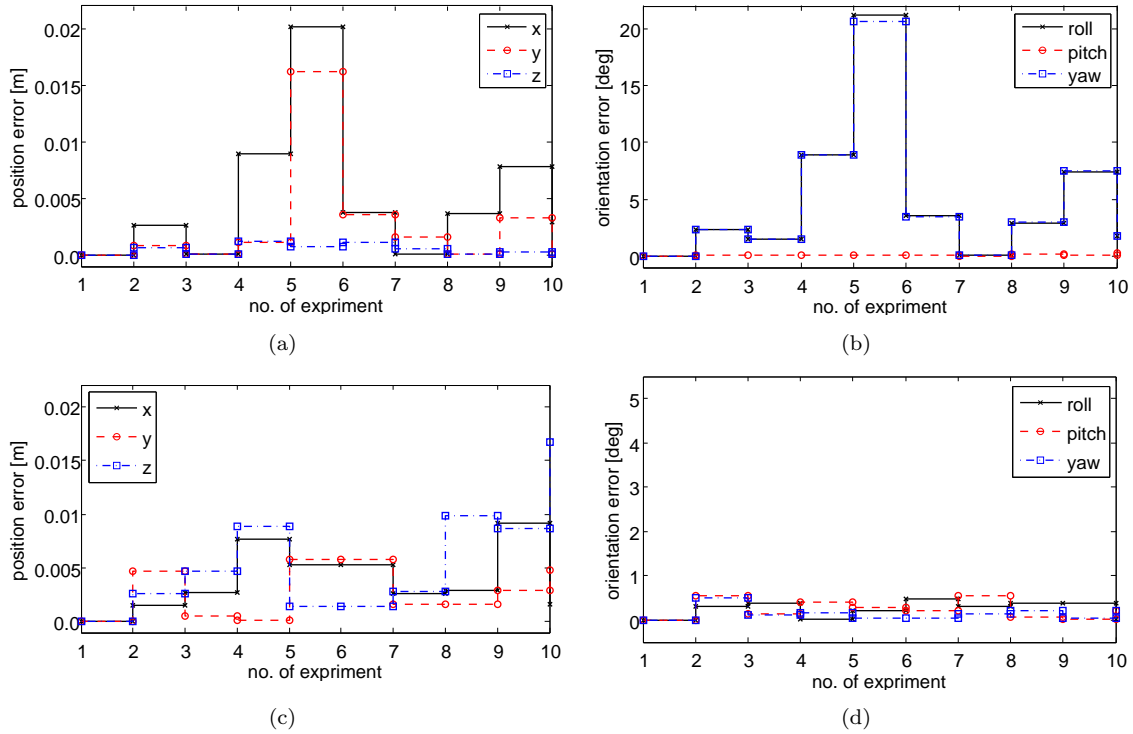
dependent on distance as well as angle between camera and marker. For the calibration setup used in FRIEND and according to [1], the marker detection accuracy has a low systematic error and low standard deviation.

In **Figure 4** the on-line recalculation of  $\frac{C}{W}T$  is represented by the feedback loop within the camera calibration chain. The input to the ARToolKit pattern detection method is a binary image containing the segmented calibration pattern. Since the success of pattern detection within ARToolKit and the accuracy of 3D pose estimation depend on the quality of the segmentation of the calibration pattern, the robust closed-loop segmentation method introduced in [5] is used. The goal of the method is to obtain a reliable binary segmented image independent on illumination conditions. But the processing speed of the calibration chain has to be high enough in order to cope with the vibration frequency of the wheelchair. So a compromise between accuracy and speed of the algorithm has to be found. Taking into account the image acquisition speed of the calibration camera of maximum 25 Frames per Second (FPS) and the time required by the image processing algorithms to perform a good segmentation and to track the visual pattern, a value of 15Hz was achieved for the calibration loop, which is sufficient for on-line adaptation of the transformation  $\frac{C}{W}T$  such that the results of 3D object reconstruction obtained from images acquired through the global stereo camera are kept precise for reliable object manipulation.

### 4 Performance evaluation

The experimental setup in which the proposed system calibration is used consists of an all-day-living scenario (ADL) in which FRIEND operates. The objective of the tests is to evaluate the impact of the suspension system on final 3D object reconstruction. In **Figure 5(a,b)** measured results representing variation of the pose of the global stereo camera with respect to the world coordinate system are shown. The values in the diagrams represent the difference between the initial pose of the stereo camera, before system functioning, and the current pose obtained through on-line system calibration.

In order to evaluate the precision of calibration, for each pose of the global stereo camera from **Figure 5(a,b)** the 3D pose of an object of interest has been calculated. In **Figure 5(c,d)** the difference between the real pose of the object, manually obtained, and the one calculated through the vision system of FRIEND has been displayed. As it can be seen from the graphics, despite the disturbances due to the suspension, the error in the calculated object 3D



**Figure 5:** Influence of spring suspension to the stereo camera pose with respect to world coordinate system: (a) position, (b) orientation; corresponding error in estimated 3D pose of an object placed at a fixed location in the environment using the presented calibration technique: (c) position, (d) orientation.

pose is maintained under a tolerable error of maximum 17mm for position and  $0.6^\circ$  for orientation. All but only one error are actually maintained less than 10mm for the position. The results from Figure 5 have been quantified in **Table 1** and **Table 2**. The presented calibration technique copes the influence of the spring suspension and the obtained 3D pose values of the object are suitable enough for reliable object grasping and manipulation.

## 5 Conclusions and outlook

In this paper the calibration of the care-providing robotic system FRIEND was presented. The goal of the method is to on-line track the pose of the global stereo camera system used to understand the robot's environment, since this pose is considerably disturbed by the movements of the wheelchair due to the spring suspension. Using a high enough processing rate for the camera calibration chain, accurate object recognition and 3D reconstruction for the purpose of collision-free manipulation path planning and object grasping can be achieved. As future work, the integration in FRIEND of a local camera mounted as an eye-in-hand configuration on the end-effector of the manipulator arm is considered. The purpose

of this camera is to improve object grasping by recalculating the pose of the object to be grasped when the manipulator is approaching it. Taking into account this enhancement, the calibration concept has to be extended in order to reliably calculate the pose of the extra coordinate system introduced and the transformations between the global and local camera systems.

## References

- [1] D. F. Abawi, J. Bienwald and R. Doerner: Accuracy in Optical Tracking with Fiducial Markers: An Accuracy Function for ARToolKit, In *Proceedings of the Third IEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR)*, 2004.
- [2] R. Cipolla, T. Drummond and D. Robertson: Camera calibration from vanishing points in images of architectural scenes, In *Proceedings of 10th British Machine Vision Conference*, pages 382-391, Nottingham, UK, 1999.
- [3] M. R. Driels, L. W. Swayze and L. S. Potter: Full-pose calibration of a robot manipulator using a coordinate measuring machine, In *International*

	$x$ [m]	$y$ [m]	$z$ [m]	$roll$ [deg]	$pitch$ [deg]	$yaw$ [deg]
Max error	0.0205	0.015	0.002	21.5	0.0	21.0
Mean	0.0054	0.0048	0.0011	5.175	0.0	5.125
Standard deviation	0.0188	0.0034	0.0059	6.433	0.0	6.203

**Table 1:** Statistical results of influence of suspension to camera's pose (see Fig. 5(a,b)).

	$x$ [m]	$y$ [m]	$z$ [m]	$roll$ [deg]	$pitch$ [deg]	$yaw$ [deg]
Max error	0.0092	0.0058	0.0167	0.4800	0.5501	0.5024
Mean	0.0039	0.0029	0.0057	0.1440	0.2420	0.2440
Standard deviation	0.0029	0.0023	0.0052	0.1479	0.2027	0.1479

**Table 2:** Statistical results of tracked object pose (see Fig. 5(c,d)).

- Journal of Advanced Manufacturing Technology*, volume 8, pages 34-41, 1993.
- [4] S. M. Grigorescu, D. Ristic-Durrant and A. Gräser: ROVIS ROBust machine VIsion for Service robotic system FRIEND, In *Proceedings IEEE/RSJ International Conference on Intelligent Robots and Systems*, St. Louis, USA, 2009.
- [5] S. M. Grigorescu, D. Ristic-Durrant, S. K. Vuppala and A. Gräser: Closed-Loop Control in Image Processing for Improvement of Object Recognition, In *Proceedings of the 17th IFAC World Congress*, Seoul, Korea, July 2008.
- [6] O. Ivlev and C. Martens and A. Gräser: Rehabilitation robots FRIEND-I and FRIEND-II with the dexterous lightweight manipulator, In *Restoration of Wheeled Mobility in SCI Rehabilitation*, volume 17, July 2005.
- [7] A. Jordt, N. T. Siebel and G. Sommer: Automatic High-Precision Self-Calibration of Camera-Robot Systems, *IEEE International Conference on Robotics and Automation*, Kobe, Japan, May 2009.
- [8] D.-J. Kim, R. Lovelett and A. Beha: Eye-in-Hand Stereo Visual Servoing of an Assistive Robot Arm in Unstructured Environments, In *Proceedings of IEEE International Conference on Robotics and Automation*, Kobe, Japan, May 2009.
- [9] S. Kim and S.-Y. Oh: Hybrid Position and Image Based Visual Servoing for mobile robots, In *Journal of Intelligent and Fuzzy Systems*, volume 18, pages 73-82, 2007.
- [10] Z. W. Kim: Geometry of Vanishing Points and its Application to External Calibration and Realtime Pose Estimation, University of California, Berkeley, 2006.
- [11] P. Lamb: ARToolKit software library, <http://www.hitl.washington.edu/artoolkit/>, [Online; accessed 28-July-2009].
- [12] P. Malbezin, W. Piekarski and B. H. Thomas: Measuring ARToolKit Accuracy in Long Distance Tracking Experiments, In *1st International Augmented Reality Toolkit Workshop*, Darmstadt, Germany, September, 2002.
- [13] G. L. Mariottini, D. Prattichizzi and G. Oriolo: Epipole-based visual servoing for nonholonomic mobile robots, In *Proceedings of IEEE International Conference on Robotics and Automation*, New Orleans, LA, April 2004.
- [14] Y. Meng and H. Zhuang: Autonomous robot calibration using vision technology, *Robotics and Computer-Integrated Manufacturing*, volume 23, pages 436-446, 2007.
- [15] Y. Meng and H. Zhuang: Self-Calibration of Camera-Equipped Robot Manipulators, In *The International Journal of Robotics Research*, volume 20, pages 909-921, 2001.
- [16] D. Ojdanic and A. Gräser: Improving the Trajectory Quality of a 7 DoF Manipulator, In *Proceedings of the Robotik Conference*, Munich, Germany, 2008.
- [17] F. Remondino and C. Fraser: Digital camera calibration methods: considerations and comparisons, In *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, volume XXXVI, Dresden, Germany, 2006.
- [18] S. Siltanen, M. Hakkarainen and P. Honkamaa: Automatic Marker Field Calibration, In *Proceedings Virtual Reality International Conference (VRIC)*, pages 261-267, Laval, France, April 2007.
- [19] H. W. Stone: Kinematics modeling, identification and control of robotic manipulator. Ph.D Thesis, Robotic Institute, Caregie Mellon University, 1986.