Discussions on the Camera-Aided Calibration of Parallel Manipulators

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1 Introduction

A parallel manipulator has two or more serial branches that connect the mobile platform to the fixed base. Parallel manipulators have closed-loop kinematic chains, where each chain contains links connected to at least two other links through joints. Because of the closed loop, some of the joints of the parallel manipulator are not actuated/sensed.

By controlling the actuated joints, robot manipulators are driven to different positions and orientations (poses) within their workspace to complete certain tasks. However, there is always a difference between the commanded pose and the actual pose achieved by the end effector of the manipulator, which is called the accuracy of the manipulator. Calibration is employed to improve the accuracy of a manipulator by identifying a more accurate relationship between the joint transducer readings and the actual pose of the end effector. Calibration also allows the robots to be programmed off-line, to move precisely to an un-taught pose and to share programs with other robots.

There are four steps of manipulator calibration: (1) construction of a model that contains a set of parameters to determine the relationship between the joint displacements and the end effector pose, (2) precise measurement of the manipulator poses, (3) identification of the unknown kinematic model parameters of the manipulator from the pose measurements and manipulator joint displacement readings, (4) compensation for the model errors in the manipulator controller.

Manipulators can be made more flexible and adaptable by incorporating other sensors such as vision into the feedback control loop. This article is a discussion of the various approaches of vision-aided calibration techniques that can be applied to most parallel manipulators. It is intended to give a preliminary reference to researchers who are considering camera-aided calibrations of parallel manipulators.

2 Calibration of Parallel Manipulators Using Vision

Camera can be used as an intactile pose measurement sensor in the second step of manipulator calibration. Compared with laser interferometers, vision system does not require critically controlled and expensive environment. Vision allows monitoring the pose of the end effector in motion provided that the image processing is fast enough.

2.1 Camera set-ups

Two different camera set-ups can be used for the calibration of manipulators, moving camera set-up and stationary camera set-up.

Moving camera set-up. In this case, a camera or a pair of cameras of the same nominal optical characteristics is mounted on the end effector (so called eye-on-hand system) or on a moving platform.

Zhuang and his research group extensively studied eye-on-hand calibration system for serial manipulators [1]. This set-up allows accurate pose measurements because the field of views of the cameras can be made sufficiently small. However, since the camera(s) moves with the manipulator, it can only perform local measurements. A precision calibration fixture should be placed in the manipulator environment to provide reference of the pose of the end effector with respect to the environment. Another disadvantage is that mounting cameras on the manipulator is invasive thus this set-up cannot be used in certain applications, such as using manipulator to pick up erosion materials. If only one camera is mounted on the end effector, the camera should be recalibrated at each manipulator measurement configuration. If two cameras are put on the end effector, the cameras are independently calibrated only once before the manipulator calibration.

Cameras can also be mounted on a moving platform. This method uses the principle similar to human or animal’s eyes-and-hand set-up. When the hand/manipulator reaches for an object, eyes/cameras can follow the position of the hand/manipulator and identify the relative position of the hand/manipulator and the object. A moving platform provides the cameras of the orientation (and possibly translation) to trace the end effector.

Stationary camera set-up. This set-up has been used in vision-aided inspection for some years. It can be used in parallel manipulator calibration because parallel manipulators have smaller work volume compared to serial manipulators and their working environment is more predictable than mobile robots. In this case, cameras are fixed outside the manipulator workspace so that when the manipulator moves, the cameras can view the features on the manipulator. One advantage of the stationary camera set-up is being non-invasive. The other one is that this setup does not require fixtures. The major problem is that there is always a tradeoff between the field-of-view and accuracy.

Stationary camera set-up can also be categorized into one camera approach and multi-camera approach. If only one camera is used, image processing is faster. However, the depth from the end effector (mobile platform) to the camera is difficult to recover. Triangulation could be used only when the optical axis of the camera is perpendicular to the line between two markers knowing the focal length of the camera, the distance of two markers in 3D, and the distance of two markers in the image plane. When two cameras are used, the depth info can be directly extracted and also this camera setup decreases the possibility of not seeing certain markers at certain pose.

2.2 Markers setup

The pose of the end effector can be measured by camera through recognizing features on the mobile platform. Geometric features of the manipulator, such as links and joints, can be used as recognizing features. However, for a parallel manipulator, one or more branches could be blocked from the view of the camera, so putting markers on the mobile platform is a better idea for parallel manipulator calibration.

Three markers on the mobile platform are sufficient to express the position and orientation of the platform. However, up to four solutions will be obtained by investigating only three points [2]. Using three points is also vulnerable to noise and measurement error. Therefore, four or more points are used in practical applications. In general, more points can minimize the measurement error, but the computation time would increase.

2.3 Parameter identification

Identifying the unknown kinematic parameters of the manipulator is equivalent to minimizing an objective function subject to constraints. The objective function is taken as the integral of error, δ, over the entire workspace of the manipulator. The error is described as the Euclidean norm of the difference between the measured value of the manipulator at discrete positions and the kinematically calculated value ($\delta = \|\text{measured} - \text{calculated}\|$). The kinematically calculated value is expressed in terms of the ideal link and joint parameters of each robot plus the possible errors from manufacturing. The followings are some of the error functions that can be applied to camera-aided calibration of parallel manipulators.

Joint displacement approach. The objective is to minimize the error between the joint transducer reading and the joint displacement calculated from the inverse displacement analysis based on the positions of the markers on the mobile platform measured by camera.

There is no closed-form expression for joint displacement in terms of the position of the branch end point unless there are three consecutive joints intersecting at one point or parallel to one another in the branch [3]. Even in a Stewart platform case, where there are three intersecting joints in the ideal situation, the actual joints may not always intersect because of manufacturing tolerance and assembling error. Moreover, there is no guarantee that every unknown parameter of each branch will appear in the expression of sensed joint displacements. Thus the error function might not be sensitive to some of the parameters.

End effector pose approach. This is the most common error function used for the calibration of serial manipulators. The objective is to minimize the error between measured pose of the end effector and the calculated value from forward displacement analysis knowing the sensed joint readings.

The choice of magnitude of weighting factor between the position error and the orientation error will influence the calibration result, which makes it difficult to determine the weighting factor. The objective function can be simplified when only position errors are considered. Evidently, the drawback of this method is that the orientation of the platform is ignored.

Position of the end effector with respect to the base frame could be obtained from the average of the branch end positions. The averaging may filter the inaccuracy thus reduce the sensitivity of this error function to variations (errors) of the kinematic parameters.

Branch end point distance approach. The objective is to minimize the error between the designed distance of the end points (connecting points of the branches and the platform) of any two branches and the calculated distance from forward kinematic analysis based on the joint readings.

The error function is dependent on the two branches under consideration only. However, complete objective function should consider distances between any two-branch end points. The error functions should be minimized simultaneously.

3. Calibration Simulation

In order to eliminate the use of fixture and moving mechanism of the camera(s) in the calibration process, stationary stereo camera set-up is simulated on an example parallel manipulator with the identical geometric layout and joint displacement sensors as the FANUC F-200*i*, a six-degree-of-freedom parallel manipulator. One marker is put as close as possible to the end point of each branch on the mobile platform. Since FANUC F-200*i* has three ideally consecutive intersecting joints, it is possible to get closed-form estimates of the passive joint displacements from the measured positions of the branch end points. The branch end point distance approach is chosen for the parameters identification.

Branch end distance error has been used for fixtureless calibration of parallel manipulator before, e.g., [4,5]. However, the combination of using branch end distance error and camera is new.

References

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