

Precision Robot Calibration Using Kinematically Placed Inclinometers

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Introduction

In the field of industrial robotics, many different calibration methods exist to reduce error in the robot system. Locating the manipulator home position is a common calibration technique, which can be divided into three main categories — relative, optimal and leveling based methods. The home position of an industrial manipulator is a position where all joint angles have a pre-defined value (e.g. zero or 90 degrees), which can be transformed into Cartesian space via the robot kinematics. Large industrial manipulators, with a working range in the order of several meters, require an accurately defined home position that can be restored with repeatability in the order of 0.2mm in Cartesian space or 0.01 degrees in Joint space.

Relative calibration methods locate each robot link in a predefined position, relative to the previous link in the kinematic structure. This requires highly accurate robot parts, an expensive proposition for high volume manipulators. Optimal methods require a measurement system to measure a set of robot poses and use mathematical models of the robot kinematics to determine the link angles. The resultant home position is sensitive to the chosen calibration poses, leading to difficulties in maintaining a repeatable calibration. Leveling based techniques utilize inclinometers to position each link parallel or perpendicular to the gravity vector and provide a simple, accurate, and repeatable recalibration of the robot's home position.

In order to achieve the required accuracy using a leveling system, several key accuracy and repeatability aspects must be considered — the robot control system, the inclinometer unit and the mounting interface to the robot. The robot control system is a function of the accuracy of the motor resolvers and is expressed as the repeatability of the manipulator. This is typically of the order of 100 micrometers as defined by various ISO standards, which test the robot at a defined speed and with a defined payload. This value cannot be compensated for using a calibration system and can be considered to be a stochastic error about the chosen home position.

Testing of the existing leveling system method revealed a mean recalibration error of 1.0mm measured at the robot flange. The existing system makes use of two sensors mounted on separate right-angle plates that are placed sequentially on various mounting plates bolted to the robot structure. Each joint of the robot is then manually jogged until the robot stands in a home position that is parallel and perpendicular to the gravity vector. Analysis of the existing process revealed that placement of the sensors on the mounting plates represents over half the total error; tolerances of the right-angle and mounting plates represent over a third of the total error; with the remainder considered to be stochastic.

Kinematic Design of Prototypes

The inclinometer unit was designed in three successive stages in order to progressively prove the feasibility of various aspects of the concept. The first cube prototype, shown in [Figure 1](#), involved mounting both sensors to a modified right angle plate. The robot mounting plates were retained and the measurement process automated via software. Although it was constructed essentially to prove the automation concept, the system also yielded a slightly improved recalibration error by eliminating the error due to manual jogging of the robot and eliminating one of the right-angle plates.



Figure 1: Initial prototype

To improve the accuracy and repeatability of the mounting procedure, the second prototype was designed based on kinematic, or exact constraint, design principles. The new design comprises an integrated inclinometer unit and separate V-groove mounting interface plates bolted to the robot structure. The inclinometer unit consists of three plates accurately mounted in an open-cube structure, with three spheres placed on the outer surface of the bottom and front plates. Each set of spheres is arranged in a standard circular kinematic coupling arrangement as shown in [Figure 2\(a\)](#), with the original prototype shown in [Figure 2\(b\)](#).

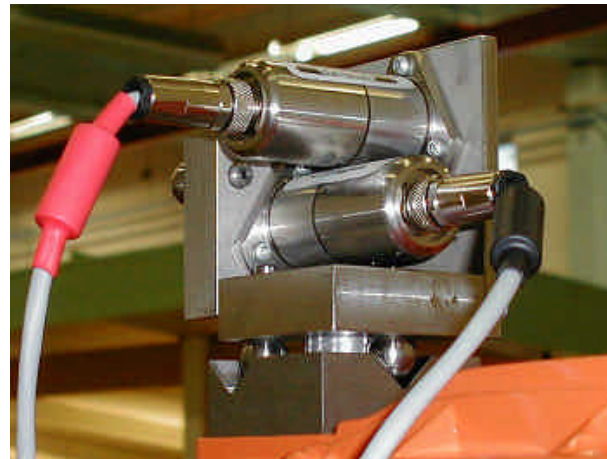
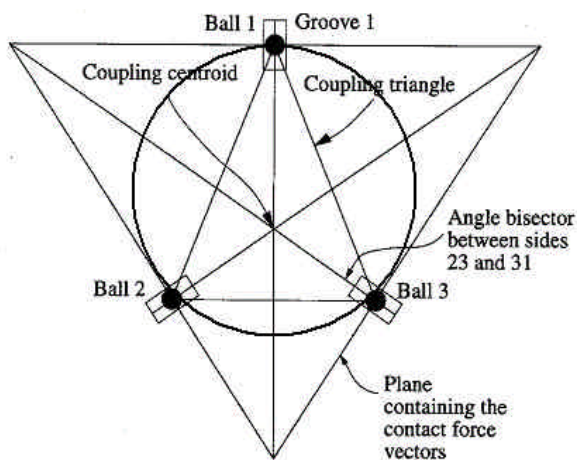


Figure 2: (a) Standard Kinematic Coupling Schematic and (b) Prototype

At the center of the circle, a magnet provides the necessary attractive preload between the cube and the robot to secure the contact between the spheres and the 90-degree V-grooves. The supplied magnet preload (approximately 35N) is sufficient to secure the unit to the robot, but is minimized to keep the Hertz contact stress under 50% of the material limit. To provide optimal repeatability at a reasonable cost, the balls and grooves were chosen to be readily available hardened steel tooling balls.

Mounted inside the cube, two inclinometers measure the roll and pitch angles with respect to the gravity vector. A “dynamic V-groove” variation, shown in [Figure 3](#), is used for axes that are not subject to gravity (e.g. the first axis), converting axis rotation parallel to gravity to a rotation that can be measured by the inclinometers. Furthermore, the design of the groove-sphere interface causes large inclinometer measurements from small axis motions, resulting in improved calibration accuracy. This is particularly important for larger robots where a small angular error is dramatically magnified at the robot flange resulting in large positioning errors. A concern for the dynamic measurement is the instability caused by excessive movement of the coupling halves relative to each other, causing separation of the cube from the V-grooves. However, the required working range of the relative motion was sufficiently less than required to reach the instability point.

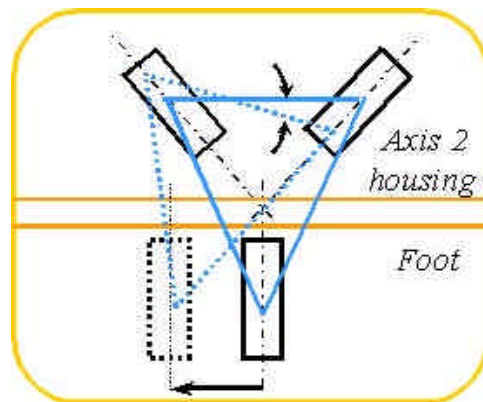


Figure 3: Dynamic first-axis calibration

The mounting repeatability of the kinematic coupling interface offers micrometer accuracy for both horizontal and vertical placements. Variation between cube individuals represents the largest source of error, predominantly due to the machining tolerances of the three cube surfaces, which can account for more than the desired 0.2mm recalibration error. This was the key issue addressed in the design of the product prototype shown in [Figure 4](#), which utilizes a single piece of Aluminum as the chassis for the cube. Only three outer surfaces are required to be accurate hence enabling the entire cube to be machined in a single pass with an NC milling machine. Furthermore, the mounting of the sensors on the outer surface of the cube reduces the size of the structure to approximately that of a credit card, reducing weight and allowing the cube to be used on robots with smaller accessible calibration areas.



Figure 4: (a) Product prototype and (b) size relative to credit card

The product prototype is integrated with existing large robots through an add-on kit wherein the V-groove plates are permanently bolted to the robot structure. For optimal cost and performance V-grooves are directly machined into the robot structure on newer robot models. The results of recalibration tests satisfy the original specifications, revealing an error of 0.2mm, which represents a five-fold improvement on the existing system.

Key words: robot calibration, kinematic coupling, inclinometer, leveling devices

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