Robot Calibration

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INTRODUCTION

Although robots are made with precisely machined parts, many small errors in the mechanism during manufacture or assembly may contribute to large errors in the final arm pose. "Calibration" is a procedure for determining these errors by measurement so a robot controller can compensate for them. Typically they are measured by inference: the uncalibrated robot pose is compared with the expected pose for a robot without errors (ideal pose) and the errors are inferred from a number of such measurements. The inferred errors are then used to define a kinematic model of the robot, which can be used to control the robot pose with greater accuracy.

Robot calibration is conducted to identify actual robot control parameters so that an accurate kinematic model of a robot can be formulated for accurate control. In other words, robot calibration is a means whereby a robot can be made to move more accurately to a given xyz position and orientation by creating an improved mathematical model of the robot kinematics. It is also the process of enhancing the accuracy of a robot by modifying its control software.

ACCURACY AND REPEATABILITY

Robots are designed to be extremely repeatable but not all that accurate (repeatabilities of 0.1mm and accuracies of 10mm or worse are not unusual). Therefore, it is important that we understand the difference between accuracy and repeatability. Repeatability is a measure of the ability to move back to the same position over and over again, whereas accuracy is the ability to move to a given position. As an analogy, consider somebody throwing darts at a board. If all the darts go into roughly the same place then the repeatability is good, though it may not be the position that the thrower was aiming at, in which case the accuracy would be bad. If all the darts hit the position the thrower was aiming at then the accuracy and the repeatability are good.

Physical Errors causing Robots to be Inaccurate

The difference between the physical joint zero position of the robot and the zero position reported by the robot controller usually has the biggest effect on the robot's accuracy. Common sense suggests that errors in the zero position of joints 1, 2, and 3 will have a bigger effect on the robot positional error than joints 4, 5, and 6. We can ignore the effect of joint 1 since it is compensated for using the model calibration (see later). Additionally, experience suggests that joint 2 and 3 often have the largest zero position error because at some point in the robot's life it will have been crashed into the floor - throwing out the zero position by up to a degree.

The error in the robot zero position is often responsible for 90% of the robot positional error.

The length of the robot links usually has the second biggest effect on the robot's accuracy. When the links are manufactured there is inevitably some variation in their dimensions from one robot to the next, as well as a variation in the orientation of the joints. Within each robot controller is a mathematical model of the robot which assumes that the links on one robot are the same length as the links on another robot of the same type, and that the relative orientations of the joints on one robot are the same as on another robot of the same type.

This is not true, and this causes the robot to estimate incorrectly where its endpoint is given a set of joint angles.

It is unlikely on most industrial robots that the variation in link lengths would be more than a couple of millimeters.

The next most significant factor in the robot positional error is joint compliance. This may be thought of as factor representing the torsional spring effect at each joint, which responds to the effect of gravity each link.

Representation of the Physical Errors

The robot kinematic structure is often represented by mathematicians using DH parameters. These are simply a compact representation of the position and orientation of each joint relative to the previous joint.

There are four numbers for each joint: d, a, θ, and α.

D and a represent distances and θ and α represent angles.

Joint zero errors for a rotational joint are stored as θ values.

Link length and distance offset errors are stored as d and a values.

Relative joint orientation errors are stored as α values.

An additional parameter β is introduced for two joints which are parallel to represent any slight misalignment.

Calibration Methods

The calibration process requires a suitable mathematical model and a suitable measurement system. Any 3d-measurement system can be used to obtain measurements, which are subsequently used to create a calibrated robot model. A variety of measurement techniques for robot calibration have been investigated. The use of vision systems, theodolite systems, laser tracking systems and ultrasonic range sensors for robot calibration has been reported. However they are all expensive. While these methods have been reported with satisfactory results, the measurement techniques have seldom been appropriate for in-situ calibration of industrial manipulators. An ideal calibration method can be applied to an industrial robot and its workcell surroundings without having to modify the tool (end-effector) or fixtures. Most reported calibration methods focus on the robot itself, and require special calibration tools to be fitted. The geometry of the tool is part of any kinematic model, so changing the tool alters the model. Changing a tool may cause further pose errors if there are significant deflections due to gravity.

There is even a method for calibrating robots that does not use a measurement device but instead moves the robot to a fixed pointer using different orientations (similar to the standard method for calibrating tools) though its accuracy is not as good as that measurement based calibrations.

Most methods of robot calibration work by comparing teachpoint positions for a robot to measurements of the end of the tool relative to an independent 3d measuring device. A search method is used to find which changes in the mathematical model of the robot would allow the distance between where the robot thinks it is and where the robot actually is to be minimized. The search method is contained within the software and the robot model is updated with the changes.

Three-Point Touch and Robot Calibration

Three-point touch is a term used to describe model calibration. The robot is used as a measuring device to determine where the fixture is relative to the robot by touching three datum points on the fixture. These points are then brought back into the simulation model of the workcell and used to update the position of the model of the fixture in the simulation.

Though the three-point touch does correct for any errors in the zero position of joint 1 it does not correct for any other factors influencing the robot's accuracy. Therefore it may be that for some workcells all that is required is a three-point touch whereas for other workcells a robot calibration and a three-point touch is required.

Tool Calibration

Tool calibration is the process whereby the true xyz offset from the mounting faceplate of the robot to the end of the tool may be found. It is important that the correct offset is used in the offline simulation so that robot program it generates is accurate on the real robot.

Some applications require that the orientation of the tool should also be found.

Some robot controllers allow a user to calibrate a tool by moving its tip to the end of a fixed pointer in several different orientations. More accurate tool offsets than the robot controller can be obtained if a calibrated robot model is used.

In some situations the measuring device may be fitted to the tip of the tool. This allows to calibrate the robot and the tool in one step.

Neither tool nor model calibration require use of a measuring system.

Calibration and Offline Programming

To understand how these techniques all fit together here is a description of several differing offline programming sequences.

A) Calibration of the robot and the tool in one step : The measuring device is attached to the end of the tool. This will only be possible if the end of the tool is easily accessible.

1. A path is generated in the simulation using the model of the workcell.

2. The robot and tool are calibrated in one step (by moving the robot to 50 teachpoints and taking a measurement at each step).

3. The model is calibrated (by moving the robot so that the tip of its tool touches each of three datum points in turn) and the fixture repositioned within the simulation.

4. The path is sent to the robot as a robot program.

B) Calibration of the robot and tool in separate steps : In this situation the measuring device is attached to a point on the tool which is accessible but which is not the end of the tool.

1. A path is generated in the simulation using the model of the workcell.
2. The robot is calibrated.
3. The tool is calibrated.
4. The model is calibrated and the fixture repositioned within the simulation.
5. The path is sent to the robot as a robot program.

C) Use of a special pointer tool for model calibration : In this situation the tool is unwieldy and so we replace it during robot and model calibration with a special pointer tool.

1. A path is generated in the simulation using the model of the workcell.
2. The special pointer tool is attached to the robot. The robot and the special pointer tool are calibrated in one step.
3. The model is calibrated and the fixture repositioned within the simulation.
4. Special pointer tool is removed from the robot and replaced with the real tool.
5. The tool is calibrated.
6. The path is sent to the robot as a robot program.

D) No robot calibration : Here we assume that the robot is relatively accurate over the its working volume in the workcell.

1. A path is generated in the simulation using the model of the workcell.
2. The tool is calibrated.
3. The model is calibrated and the fixture repositioned within the simulation.
4. The path is sent to the robot as a robot program.

E) Remastering of the robot : Suppose that offline programming has been attempted without robot calibration and that the robot was found to be inaccurate. The robot is then remastered.

1. The robot is remastered using the manufacturer's remastering procedure.
2. A path is generated in the simulation using the model of the workcell.
3. The tool is calibrated.
4. The model is calibrated and the fixture repositioned within the simulation.
5. The path is sent to the robot as a robot program.

Glossary of Useful Terms

Accuracy The ability of the robot to move as close as possible to a specified position.

Calibration, model The process of finding the true position of a fixture in a robot workcell, and then updating a simulation model so that the model of the fixture is in the correct position and orientation.

Calibration, robot The process of finding the physical errors in the structure of the robot that make it slightly different to the robot controller's internal mathematical model. This improves the accuracy of offline programming.

Calibration, tool The process of finding the physical offset from the faceplate of the robot to the endpoint of the tool.

DH parameters The parameters used in the mathematical model of the robot physical structure.

Faceplate The end of the last robot link. The tool is usually attached to the robot faceplate.

Fixture An object whose position does not change during the execution of the robot programme.

Kinematics The relationship between the angles between each successive link of a robot and the xyz position and orientation representing the tool frame relative to the base frame of the robot.

Offline Indicates any process which occurs on separate computer to the robot controller without tying up the robot controller.

Remastering The process of changing the zero position reported by the robot controller to be the same as the physical zero position of each joint.

Repeatability The ability of the robot to move back to as close as possible to a specified position again and again.

Three-point touch A model calibration (see above).

Zero position The position at which all the joint values are zero.