1 Introduction

1.1. Motivation

The motivation for this work emerged from an existing manipulator used in subsea interventions. The manipulator is mounted on a ROV which brings it to its working environment at great sea depths. Every time the robot is brought to its destination its position relative to the work environment is altered. In order to estimate the position of the manipulator relative to the objects of interest, a manipulator base calibration has to be performed. To achieve efficiency and accuracy it is desired that this process is automated. There are few sensors that can endure the rough working conditions at great depths. This is the incentive for the use of computer vision to calculate the relative position and orientation of the manipulator base. To be able to alter its pre-programmed trajectories according to the estimated position, the kinematics of the manipulator need to be calibrated to give good absolute accuracy and repeatability. Therefore the calibration of the manipulator structure is carried out in a laboratory before the robot is brought to its work environment.

1.2. Work objectives

The main objectives of this work are:

- Evaluate techniques for robot calibration, and develop an exact model of the direct and inverse kinematics of the manipulator.
- Evaluate computer vision techniques, camera calibration and pattern recognition.

- Develop methods to estimate the relative position of the manipulator end-effector through recognition of features extracted from images.
- Simulate the techniques used on the robot to test the viability of the procedures through experiments.

1.3.
Work description

The goal of this thesis is to develop visual calibration methods to allow a robotic manipulator to localize itself with respect to its environment. The procedures are applied to the robot TA-40 [23] with 6 rotational joints and 6 degrees of freedom. This manipulator is used in underwater interventions and will be attached to a ROV which will transport it to its work environment. In order to execute pre-programmed trajectories from different locations, it is necessary to establish an exact model of the kinematics of the manipulator. The first step of the procedure involves calibration of the manipulator structure. It is necessary that the robot has both good repeatability and absolute accuracy. Figure 1 shows the difference between good repeatability and good absolute accuracy. Good repeatability means that one specific configuration of the joints will give the same position of the end effector independent of the previous movement of the robot. Good absolute accuracy of the robot means that the robot can calculate the precise position of the end effector for any configuration of the joints.

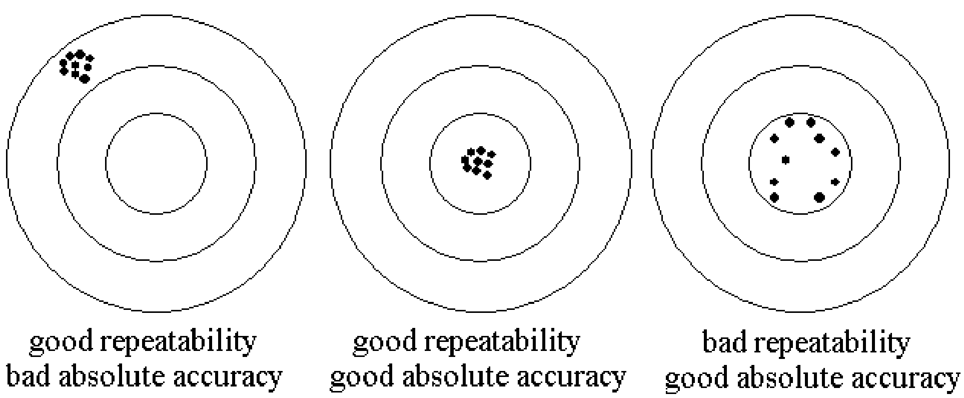

Figure 1 - Repeatability and absolute accuracy

Calibration of robots is a process where the accuracy is improved by modifying the control software of the robot to compensate the errors in the nominal measurements of the physical structure.

The calibration process can be divided into 4 steps:

1) Elaborate a mathematical model to represent the kinematic movement of the manipulator.
2) Measure the position of the end-effector of the manipulator.
3) Estimate the relation between the joints angles and the position of the end-effector.
4) Compensate the deviations between the ideal estimate of the end-effector positions and the measured positions by updating the control software.

The steps involving selection of mathematical model, identification and compensation of errors are studied in [1] and [2].

To improve the geometric model of a robot by calibration, the proposed method uses a certain number of measurements of the 3D position of the robot end-effector. Together with the measured angles of all the joints, the errors of all the joints are estimated.

Due to the high versatility of the ROV, the robot will be working in many different environments. Every time the robot is introduced to its work environment, the relative position of the robot base has to be estimated in order to be able to execute preprogrammed tasks or simply give a feedback to the operator of the robot's position by means of virtual reality.

This thesis follows modern tendencies of automation that has an increasing emphasis on robots guided by sensors, automating totally or partially many of the tasks to be executed. Cameras linked to the controller detect the actual position of the robot automatically. The control software will automatically be updated so that the pre-programmed trajectories can be executed automatically. The trajectories will be programmed with a CAD system. This means that they can be estimated in a graphic environment without using the robot, allowing a greater velocity in the validation of trajectories.

To make these techniques possible, it is necessary that the robot has both good repeatability and accuracy. This will be achieved by means of calibration of the robot structure.

Since the base of the TA-40 is mobile, it is necessary to perform a calibration of the base relative to the work environment every time the robot is used. This calibration will be done by extracting and recognizing features in images of known objects of interest. Calibration by use of cameras is automatic, potentially fast and non invasive into the work environment.

There are two possible camera configurations. The first is to mount a camera close to the end-effector of the robot allowing the operator to position the camera to get a good view of the objects of interest. The second alternative is fixing a camera or a stereo pair to the ROV or robot base, allowing a larger system of cameras to be used. However, ensuring a good view of the work environment is more difficult when the camera system is mounted in a fixed position.

The robot base calibration is divided into three stages:

- Image feature extraction
- Pattern recognition
- Estimation of the camera and robot pose

In the first stage the objective is to extract image features that are robust, meaning that they have a good ability to distinguish the objects of interest in different scenarios. To extract these features it will be used an algorithm called SIFT (Scale Invariant Feature Transform) developed by David G Lowe [3]. This algorithm has proven to be a robust method to recognize features in images. It is capable of recognizing objects in images that are taken with different camera poses. It is also robust when it comes to image noise and illumination changes.

In the second stage the feature vectors calculated by the SIFT algorithm are compared to find the right matches in the two or more subsequent images.

In the last stage the pose of the camera is estimated by triangulation. To perform triangulation it is necessary to know the relative pose between two cameras. This can be achieved by using a camera stereo pair or by using the kinematics of the robot to estimate the pose between two images. When using a stereo pair the pose estimation depends highly on the distance to the object and on the intraocular distance between the two cameras. To be able to estimate the pose relative to a distant object it is necessary to have a high separation between the cameras. To perform a triangulation between two poses estimated by the robot kinematics, the robot needs to have a good absolute precision both in translation and in rotation.

After the system is calibrated, tasks can be automated. Further, the knowledge of the absolute position of the manipulator and the work environment makes it possible to create a 3-D visualization of the environment that will give real time feed-back to the operator. This allows the operator to visualize areas that are dark or not visible from the operator's view point. The use of virtual reality makes it possible to magnify and view the operation from any angle without moving the robot, facilitating the execution of various tasks.

1.4. Organization of the Thesis

This thesis is divided into six chapters, described as follows:

Chapter 2 comprises the theory necessary for the calibration process of a robotic manipulator. A detailed description of the basic concepts of kinematic modeling is given, including homogeneous transformations using the Denavit-Hartenberg notation [4]. The kinematic error model is introduced, and the techniques used to estimate the errors are elaborated.

Chapter 3 describes the concepts of computer vision used. The technique (SIFT) used to recognize features in the work environment is described in detail. All the geometric considerations are described including camera calibration, triangulation and pose estimation.

Chapter 4 describes how the techniques elaborated in chapters 2 and 3 are implemented to calibrate manipulators such as the TA-40. The method used to calibrate the manipulator structure and the method used to estimate the manipulator pose relative to the work environment are described in detail.

Chapter 5 presents the performed practical experiments and simulations.

Chapter 6 presents comments and conclusions to the performed work.