Recent Advances in the Implementation of a Multi-Sensor Measuring System

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Abstract. We present our work on the implementation of a multi sensor measuring system. The work is part of a large scale research project on optical measurement using sensor actuator coupling and active exploration. This project is a collaboration of researchers from seven institutes of the University of Stuttgart including photogrammetry, mechanical engineering and computer science. The system consists of optical sensors which can be manipulated in position and orientation by robot actuators, and light sources which control illumination. It performs different tasks including object recognition, localization and gauging. Flexibility is achieved by replacing the common serial measurement chain by nested control loops involving autonomous agents which perform basic tasks in a modular fashion. The system is able to inspect and gauge several parts from a set of parts stored in a 3-D model database. The paper gives an overview of the entire system and details some methods to deal with datasets of inhomogeneous accuracy and resolution.

Keywords: Metrology, Calibration, Registration

1 Introduction

In the past few years we have seen a tremendous growth in the number of 2-D and 3-D vision systems for inspection and gauging. Their speed, flexibility and accuracy has made optical measurement system quite popular for many applications in industry. Currently we can observe a trend, mainly at automobile manufacturers, to replace static measurement setups with flexible measurement units using general purpose robots, which perform a series of measurements using a single sensor. This new generation of measurement systems is characterized by certain limitations. Typically they consist of only one single type of sensor, often a laser triangulation sensor. Usually the sensor can perform only a single measurement task, such as edge measurement. If several of these systems are combined to form a larger set up, they perform their task independently and without interaction. All motions are pre-programmed, usually they have been taught by hand. The system performs repetitive measurements of a single class of objects. It is our and our partners vision to design a system which is to overcome these limitations. We aim at implementing a highly flexible measurement system using several different types of sensors. Flexibility to us has two meanings, for one we wish to be flexible in what we measure i.e. the kind of objects we aim at and second in how we do it i.e. what sensors we use. Our system is not designed for a single class of objects but for a large variety of objects varying in size, shape and material. Using different types of sensors we exploit the possibility of combining sensors and illumination devices such that we achieve the optimal setup for the specific task. The single steps of a measurement sequence shall not be chosen by hand but are to be computed automatically on the basis of a given CAD model and the ability to actively explore the scene.

2 The Project

The goal of our work is to implement an optical measurement system flexible enough to handle a large variety of objects from the industrial world. Using different types of sensors, e.g. mono cameras, stereo cameras and stripe projection systems, the measurement process is automatically tailored towards the object presented to the system and measurement tasks specific to the object are executed. A CAD model for each object forms the basis for measurement planning and assessment. We allow the objects to be presented to the system in arbitrary position. The system has to recover the pose of the object automatically. The goals of this project are rather ambitious and the issues to be resolved are from a broad range of scientific areas. It is not possible to attempt to implement such a system without interdisciplinary collaboration. It is for this reason that the University of Stuttgart has established a large scale research project funded by the German Science Foundation. The project is a cooperation of seven institutes of the University from all major areas of engineering: mechanical engineering, electrical engineering, optical engineering, computer science and photogrammetry. The different disciplines all have contributed their specific capabilities and know-how for the broad range of issues:

- mechanical design and robotics for sensor positioning
- sensor technology, optics and lighting technology
- CAD technology, measurement planning
- Software system design, distributed computing and machine learning
- sensor and actuator calibration, high precision imaging
- image processing, object recognition and modelling.

Altogether more than 15 researchers are occupied with this project. In addition a large number of students is involved.

(a) (b)

Figure 1: (a) The measurement cell and (b) a view inside the measurement volume with one of the sensors in the front and a part in the back.

3 System Design

3.1 Actuators

We have created a test bed in order to validate our concepts in real-world experiments and to be able to refine and improve our measurement strategies. At the moment our experimentation environment consists of a portal machine (see Figure 1) which uses linear motor like drives to move three independent platforms within a measurement volume of approximately 1 m^3. The platforms are hanging upside down from the ceiling of the measurement cell, attracted to the ceiling by permanent magnets but floating on thin air cushions. Electric magnets are the drives which move the platform along a regular grid engraved onto the metallic ceiling. The grid on the ceiling forms a two dimensional coordinate system along which the platforms can be positioned with high repeatability and accuracy. Each of the platforms is equipped with a serial link arm. The number of axes ranges from one to three. Three platforms independently moving in two axes, one with a single, the other two with three additional axes total a system with 13 axes. The complexity of the machine has several implications. For one the possibility of moving three platforms independently within a common volume allows for a number of sensor interactions and combinations. The high number of controllable axes creates the possibility to position the sensors in a very flexible way. This makes it possible to move the sensor to its optimal position with respect to the measurement task. Sensor positioning can be vital in cases of reflecting surfaces or complex shaped objects. One of the drawbacks of the complexity in the kinematics of course is the increased complexity in motion computation. Advanced algorithms of motion planning, collision avoidance and kinematics in general have to be applied. Bringing all the separate modules into one and the same coordinate frame becomes a major issue when measurement results obtained from different sensors have to be merged and evaluated.

3.2 Sensors

The idea behind designing a multi sensor system is the possibility to choose from an assortment of sensors the ones which are best suited for a particular task, depending on several conditions such as object size, shape, material and desired accuracy. The sensors should not have to much overlap in their capabilities but rather complement one another. The fundamental requirement of not knowing the objects initial position on the one hand and the desire of high accuracy on the other gives the need for a wide range of sensor resolutions. Initial object localization can only be achieved if a sensor is available which can inspect a large portion of the measurement volume. On the other side we can achieve high accuracy best when the sensors field of view (FOV) is narrowed down to the part of the object to be inspected.

At the current stage we have integrated three sensors in the mechanical platform and we have developed a fourth sensor which will possibly be integrated in the future. A motorized zoom lens camera which has the largest FOV of all of our sensors is mainly used for object localization and active exploration of unknown scenes. The cameras focal length can be varied in a broad range. In addition it has a large range of focus. The cameras FOV starts at 26 *mm* distance where it is able to achieve a resolution of 21 lines per *mm* at maximal focal length. At the other end, at a distance of 1 *m* (the maximum within our mechanical platform) it reaches a FOV of 960 *mm* x 720 *mm*. This makes it ideally suited to inspect any kind of object independent of its size. In addition the camera has both a motorized focus and iris. Further camera parameters such as exposure time and gain can also be remotely controlled. These features make it our most flexible sensor. Several algorithms like an auto-focus algorithm as well as an auto-iris and an auto-FOV algorithm have been implemented to exploit this flexibility. The auto-FOV adapts the cameras focal length so that the object is imaged at its maximum size occupying the whole of the cameras imaging sensor. While a zoom lens camera with motorized lenses gives great flexibility we also have to mention some of the disadvantages. The optomechanic accuracy of a motorized lens can not be compared to that of a fixed focus lens. We observe slight deviations in the repeatability of the motor positions. This leads to measurement errors with a standard deviation of up to 1.7 μm in image space at a pixel size of 6.7 μm.

The second sensor is a high precision stereo camera. The cameras are high resolution (1k x 1k) digital cameras equipped with 17 *mm* focal length quality lenses. The stereo head has a calibrated fixed base length. The sensor is used for precise 3-D measurement of distinct object features such as drill holes, edges and corner points. In combination with a stripe projector it can also be used for large FOV dense surface measurements. The third sensor is called LASCAM (laser camera) and consists of a laser stripe projector in combination with a CCD camera. The sensor is used for dense 3D surface measurements with a smaller FOV of 40 *mm* x 40 *mm*. The fourth sensor which is currently not integrated in the machine is a stereo stripe projection microscope. It uses one optical path to project a stripe sequence and the other for image acquisition. It is capable of taking dense range images of a very small area down to 1 mm^2, useful for detection of small surface defects and to determine surface roughness.

3.3 Software Architecture

The large number of hardware components, actuators, sensors and lighting devices, raises the need for a large number of software components for hardware control and processing. Some of the software is specific to some hardware and has to be adjusted whenever hardware changes other software is of more general use. The experimental character of our system implies constant change and therefore calls for an adequately flexible software system design.

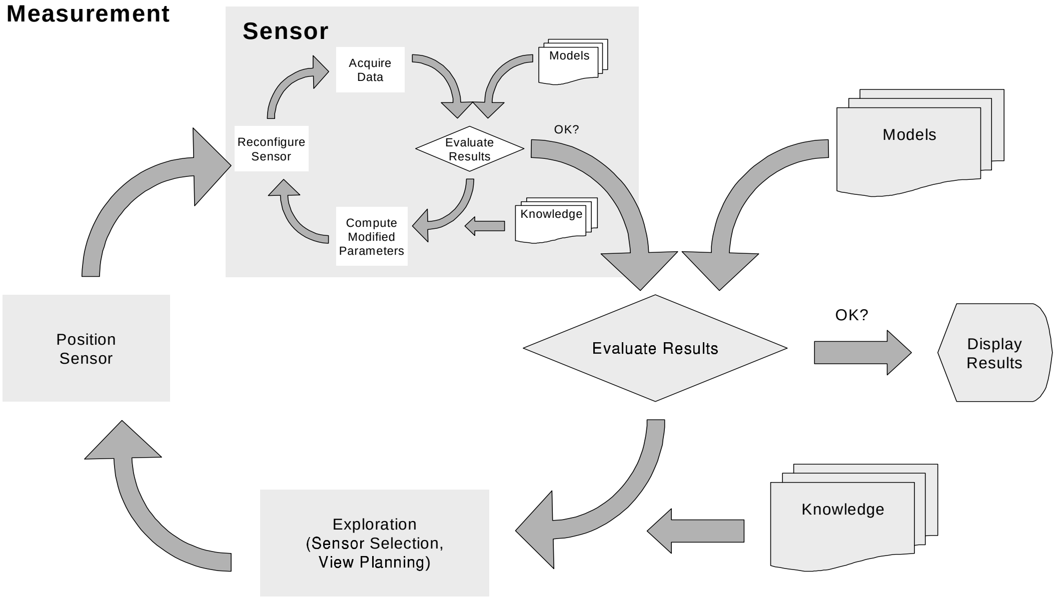


Figure 2: Example of a nested control loop.

A monolithic software structure is not sufficient for our purpose. Likewise the amount of parallelism inherent in the system, for example parallel movement of the sensors, parallel movement and image acquisition or processing, calls for a software system design which allows for distributed computing rather than the classical sequential approach. We have successfully designed and implemented a distributed object oriented software architecture based on industry standard CORBA (Common Object Request Broker Architecture) [7]. CORBA is available cross-platform and so we are able to combine different computing platforms within one system which eases development. Within the CORBA framework we establish so called autonomous agents [6] which can offer services and also request services from other agents. The autonomous agent concept encapsulates software components specific to certain hardware and can be easily updated or replaced when hardware changes. The concept has proven to be an excellent tool to cope with the problems of a large and complex system.

4 Calibration, Data Acquisition and Processing

The described multi-sensor measuring system offers new challenges but also the capability of performing new measurement tasks. In the past, we successfully demonstrated automatic object localization [3] and object recognition [2]. The main focus of this paper is on industrial inspection. In this context the inhomogeneous quality of the data is a very important aspect of such a system. The entire inspection process comprises many different steps like data acquisition, registration, integration, feature extraction and actual/nominal comparison to name just a few. Some of these steps are probably iterated a few times using either the same sensor or even different sensors. To guarantee a certain level of accuracy for the results of a measurement task, information about the quality of the data becomes a vital issue. The quality of the data is represented by means of covariance matrices, which are individually assigned to the measured data points, and propagated through all processing steps. In the remainder of this section, we present a typical processing chain for the inspection of free-form surfaces.

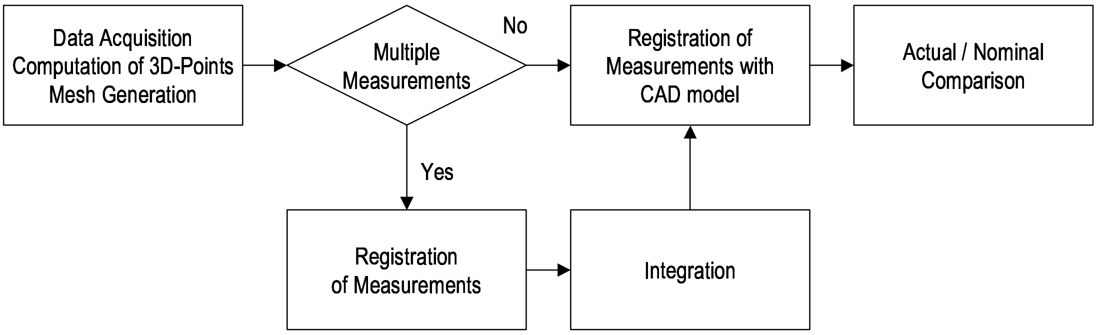


Figure 3: Typical processing chain for shape inspection using dense surface measurements.

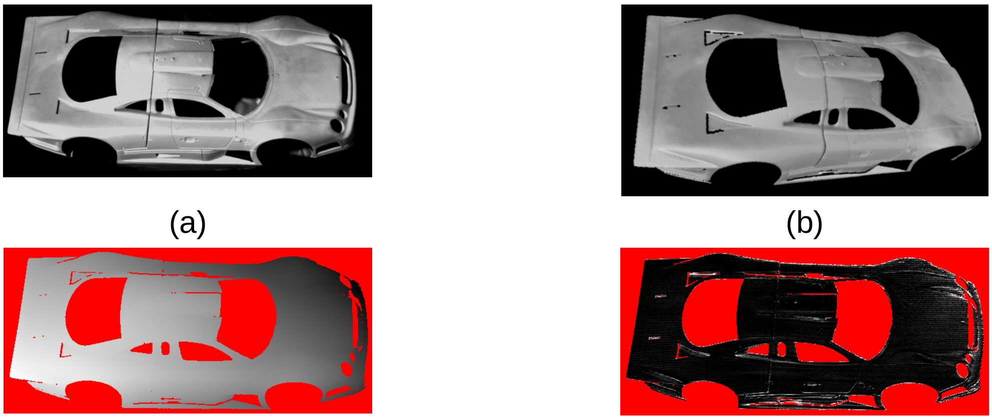
4.1 Calibration

Calibration is probably the most fundamental aspect in the implementation of any measurement system. However, it’s importance and complexity is often seriously underestimated. In this context calibration means both, sensor calibration as well as the calibration of the machine itself. Actuator calibration is necessary to determine the geometric relationship among the measurement machine, the different sensors and a reference frame.

In our case, the reference frame or world coordinate frame is located in the base plate of the measurement cell and is represented by a number of targets that are known with high accuracy. The base coordinate frame is located in the ceiling and was provided by the manufacturer. It is the coordinate frame, to which all transformations inside the machine refer to. The kinematic model of the machine allows us to transform from the flange coordinate system, which is defined on the mounting surface of the end-effector, to the base coordinate frame. The sensor coordinate frame is the natural coordinate frame for raw measurements. It is linked to the flange coordinate frame by the hand-eye transformation. At the moment, we assume the base to flange geometry to be accurate and stable. Hence, we are only concerned with the identification of the base and hand-eye transformations which can be computed from a set of images, where the exterior orientation has been modified in such a way that the desired parameters can be computed. Sensor calibration is performed using the concept of self-calibration from a few measurements of a planar test field. The test field features a number of unique targets, which can be identified automatically and allow for a fully automatic measurement procedure. The calibration parameters are computed by the *Australis* bundle adjustment package from the department of Geomatics of the University of Melbourne.

4.1 Data Acquisition

Dense 3-D surface acquisition can be performed by active triangulation using one of the stripe projection systems. The projection devices are modelled as inverse cameras making it possible to apply standard photogrammetric techniques for calibration and processing. Various algorithms have been developed to allow for the simultaneous acquisition of multiple cameras and to compensate for systematic errors apparent in traditional methods [5]. One of the most important properties of the measurement system is the availability of covariance information for each measured point (Figure 4). The inherent redundancy can be used to discard inconsistent measurements if large residuals are encountered. Observations from multiple cameras can also be used to enforce explicit consistency tests. Specular reflections, as they are likely to occur on the surface of machined metal parts, cause spurious 3-D point measurements. The consistency tests are based on the observation, that specular reflections are viewpoint dependent. If the cameras view the object from different angles we can compute the deviation between object points, computed from different pairings of image points. This allows us to either discard one single observation or completely discard all the observations for the corresponding surface point.



(a) (b)

(c) (d)

Figure 4: (a) Intensity image of a scale model of a car body. (b) Rendered view. (c) Coordinate image containing the Z component. (d) Covariance image of Z component. Surface discontinuities show up clearly as light areas indicating larger errors.

4.2 Registration and Data Fusion

The variety of sensors within our system implies that measurements differ in size, resolution and accuracy. For this reason, the integration of inhomogeneous datasets into one common surface description is very important. Registration of 3-D data is performed using extended versions of the iterative closest point algorithm (ICP) [1], which directly work on triangular meshes. The vertices have additional attributes like color and covariance information. Our implementation uses covariance information to choose appropriate weights for the point correspondences and hereby accounts for differences in the quality of the acquired data. We have developed different algorithms for the pairwise registration of two datasets, as well as the simultaneous registration of multiple datasets [4]. The registration process is an iterative procedure, thus initial values are necessary to guarantee proper convergence. As the sensor orientation is known from the forward kinematics of the machine, good initial values can easily be provided.

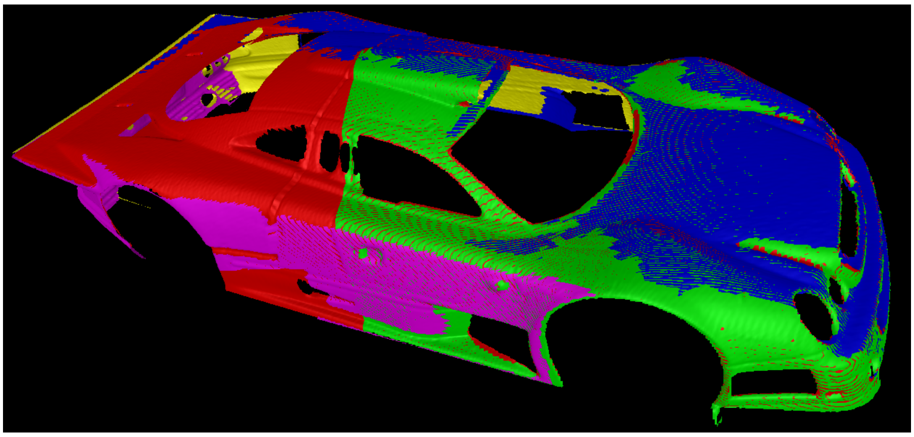


Figure 5: Reconstruction of car body from 5 different views which have been aligned using our multi-view registration technique.

4.3 Validation

In order to check whether a machined part meets its specification, the datasets are registered against their CAD model and the deviation between the measured points and the CAD model is computed. The availability of covariance information makes it possible to decide whether the observed deviation is significant or within the noise level. Based on the results of a statistical test, color can be assigned to each measured point according to a traffic-light model where red represents a significant error, green means that the deviation of the point is within the specification and yellow indicates that this area needs further inspection.

6 Summary

We presented the overall concept of our project on a measurement system for inspection and gauging of industrial parts. We detailed some of the calibration, data acquisition and processing tasks and presented the results obtained from test runs. In combination, these tasks form a complete chain from data acquisition to part validation. To cope with inhomogeneous data from different sources covariance information is used in each step to choose appropriate weights and to determine the uncertainty of the computed results. The development of the system is an ongoing process and we will work to increase the degree of automation and the spectrum of measurable features.

7 Acknowledgements

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