Path detection, estimation and correction for robot guidance

Abstact of the PhD thesis

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This thesis proposes new methods for robot path correction. These methods are targeting applications of visual beads on wing parts, such as doors, fender, trunk lids, etc.

Since such applications require a high demand of accuracy next to quick cycle times, the methods presented are not only targeting the path correction alone, but also improvements of feature detection, calibration, and sensor images. Therefore, this thesis introduces a method for detecting noise points within the images of laser stripe sensor, by applying statistical methods based on Brownian motion with drift.

Furthermore, in order to improve feature detection with an acceptable speed, we present a method that combines an Em-ICP with the Douglas Peuker algorithm to achieve much higher execution speed. Finally, the core of this thesis is an algorithm to determine the 6-dimensional correction of the application path of a robot based on sparse stripe scans. The final topic this thesis addresses is how to make these methods applicable within visual servoing applications. This includes a new approach to motionless calibration for laser stripe sensors and also an adaption of the path correction algorithm in order to provide relative measures.

Chapter 1:

Chapter 1 is an introduction to the contents of this work. It starts out with a short overview of the historical development of automation to the actual modern industrial production sides today. Further is gives a short introduction to vision systems, about their purpose and what they are doing. This also includes an overview of the prevalent sensors in application for vision system, namely cameras and laser line sensors.

It also introduces to the history of production lines, which is starting out with the ideas of Frederick Winslow Taylor, who searched for multiple ways to improve industrial production outcomes [1], continues with Henry Ford, who was building the first automotive production lines up to modern production lines, today. This chapter also introduces the origin of the “idea” of robotics, originates by a play of Karel Capek (”Rossum’s Univeral Robots (RUR)”) [2] and what the robots became today.

Especially the robots get a lot of focus within this chapter, due to their central role in this work. This is not only, by means of the historical background, but also by giving some insight of their working principle. This includes at first the terminology which is used in the context of robotics, like tool, frames, poses etc. and continues with their technical features and construction philosophy like e.g. SCARA robots. Some central technical concepts will be mentioned like the concept of forward transformations or “Denavit-Hartenberg-Transformations”[3] . And finally, the reader will also be able to find out why it is beneficial after all to employ robots in production lines.

Another section within the introducing chapter sheds some light on how modern car plants are constructed. It introduces the different departments inside an automotive production plant, which are:

- The press shop

- The Body shop
- The Paint shop
- The Assembly shop

And gives a short overview how they function together. It also explains the production buffers, which are common the secure the production in modern car plants.

Also one topic, which got a special focus within this chapter, are the transportation lines, the so called conveyors, and the different types of transportation units, called skids, which run on the conveyor. This is due to the fact, that the inaccuracy of most conveyor system is one the major reasons for the need of vision system helping the robots to find the accurate position of the cars.

Finally, it serves a short overview about the contents of this thesis. It highlights some the problems of sealing bead close to reference edges and helps the reader understanding why it is necessary to develop a more potent system for robot guidance. This is done by working out some arguments, by the example of sealing beads in the inner side of the door, where the metal sheet from the front gets crimped around the back side and gets sealed by a visual bead.

Chapter 2:

This chapter tries to present the technical foundations to the reader. It starts out with simple cameras by explaining the pinhole camera model, which is the mathematical foundation of a camera representation. This will give the interested reader an insight about how the mathematical model behind a camera works and how the two-dimensional image features will be transferred into the three-dimensional world. The understanding of such models is essential for the further understanding of the work, as it follows. Since in the contribution about the camera calibration in chapter 4 also requires an insight about the lens distortion, as well as their calibration, all necessary technical foundations about lens distortion are also explained within this chapter. Therefore, the reader gets in touch with the thin lens model, which is employed to construct a lens model to approximate the lens distortion which is overlying the images as it was formulates by Brown-Conrady [6,7] .

Building on these foundations, the reader gets a deeper insight into the techniques of camera calibration and the underlying mathematics. He will learn about the differentiation between intrinsic and extrinsic parameters and gets in touch with the theory of calibrations. Afterwards it describes a whole step by step scheme of the calculations necessary to calibrate a camera by direct linear transformation (DLT) [8,9].

Building up on the model equations for the camera, the reader will get some insight about how it is possible to measure with cameras and how the different techniques work. The idea of rays, which will be calculated based on the previously introduces model equations, will be introduced to the reader. One will also learn about different approaches of combining these rays to measurements. One of these approaches will be the stereo principle, which is able to determine three dimensional measures in the calibration space, another will be the bundle adjust.

Following the description of the cameras, there is also an overview of laser triangulation sensors. It starts out with the point sensors and provides an overview about how such sensors are constructed with a flowing introduction to the basic geometric relations between the light sensitive array and the laser, which is necessary to determine a calibrated distance measure.

Based on this foundation the reader gets the chance to gather some insight about laser line sensors, which are close sibling to the previously explored point sensors. In a detailed overview one will learn how a laser line sensor is different and what the images such a sensor will produce are looking. Some further discussion will focus about different methods of calibration for laser line sensors, and how simple approaches just based on took up tables are possible.

The chapter continues with the structure of laser line sensor data. It discusses the limitations due to the missing degree of freedom of the scan data and how it will influence the result quality of the correction results. And it sheds some light on the possible methods of robot-hand calibration, as it is for example proposed by Zhuang, Roth and Sudhakar [16].

After calibration of the laser line sensors, one can find an introduction about robot guidance systems based on such laser line sensor and how they are working, and there will be an overview over panel fitting systems as an example.

After that chapter 2 concludes with a short overview of the state of the art, which is emphasizing the current research and proposals which have been done on this field. It details about some of the latest publications in this filed [11, 12] and give a short overview over their intentions.

Chapter 3:

Chapter 3 is presenting a “new approach for path correction” which is constructed of tree original claims of in this thesis. The first claim is “a novel statistical method for noise filtering within the sensor data”, which is introducing an algorithm for filtering outlying points from laser line scanners. Such outliers will be introduced by scratches on the scanned objects which are distributing the laser light in a way, that it will be visible as a “so to say” second line in the camera images. Since the sensor can hardly distinguish between reflections made intentionally, by the surface, or reflection mad unintentionally by being redirected du to some scratches, it will also display these wrong reflections as parts of the surface structure. It is also possible that such failure recognitions will occur due to a complex structure, big concavities for example, or by being noise on a dark surface. The algorithm proposed in this chapter is supposed to supress such appearances by employing an algorithm based on a MAP estimator which estimates the maximum probable scan positions for the sensor data, based on a log-normal assumption. Every point which is not within the calculated probability threshold are rejected as an outlier. Also, the reader will learn about the optimization of the calculation, since it was targeting be implemented directly on the scanning device.

Another original claim, introduced by chapter 3, is an algorithm for flexible contour matching. The proposed algorithm can match arbitrary, predefined contour features, into a given sensor image. It is based on the idea of the iterative closest points algorithm ICP [13], which get implemented in its more capable form, the EM-ICP introduced by Granger[14].

The EM-ICP is performing a soft assignment, since it is not only considering a singe “Nearest Neighbour” as a match for the iteration step, but instead is using multiple candidates with different weight for each iteration. However, since the EM-ICP is in its basic form too slow for the matching of the sensor data in real time, this work proposes the combination between the EM-ICP and the Douglas Peucker algorithm. By employing the Douglas Peucker algorithm [15], points will be reduced in a manner, which sorts out the points which are less beneficial for the end results quality. Since the execution time of the Douglas Peucker algorithm is rated with O(n log(n)), it results into a much faster execution performance and ensures execution times within milliseconds. The interested reader can find all implementation details, for the whole algorithm, as well as a detailed discussion of the formulas within this chapter.

The final component of the new path correction, which is proposed in this chapter, is a method to combine the different laser line sensor data, recorded at multiple measurement spots, to a correction vector. The proposed algorithm is capable of handle the point cloud data provided by the laser line scanner with all its different properties, compared to other sensor images. Further it provides some tools to avoid the resulting instabilities, caused the unobserved degree of freedom and the positions insecurities caused by the sensor triggering. The trigger inaccuracies are rooted within the way, the images are recorded, since the laser line sensor is carried on the robot's writs and gets triggered without stopping. Multiple scans for different regions of the measured object can dynamically be combined to one correction vector, which empowers the application for multiple corrections on different spots of the target object. This allows applications on deformable non rigid objects. To achieve that a global scheme of transformations for each sensor position will be derived. This global transformation will be combined with a local shift equation, which will be derived step by step within this section. After all both formulas will be coupled to a global minimization scheme, which then needs to be solved by a nonlinear least squares solver. All necessary details about least square solvers are provided later in the appendix.

Chapter 4:

Chapter 4 transmits the results of some of the proposals, made in chapter 3, to panel fitting systems. Panel fitting systems are system, which position wing parts like doors, trunc-lids, etc. into the welded body frame. They perform this task by also employing laser line sensors, which are in this cased used in an open control loop similar as for the camera-based approach, which is described in [16]. The publication [17] describes the setup of a standard panel fitting system, which is measuring the distance between the panel and the mounting frame, by two orthogonal values, called “GAP” and “FLUSH”. These values are delivered by two laser line sensors at each measurements position, which are mounted as a so called “double head”. In such a setup the laser lines of the two heads are overlapping, but sensors themselves are amounted in a 90-degree angle.

Since the frame and panel need to have symmetrical gaps and should be on the same level, they need to be positioned with high precision. Panel gaps are a huge quality feature and are therefore carefully obeyed by many customers. Also, the noise level on high velocities is strongly influenced by the gap size. Hence it is desirable to keep such panel gaps small and symmetrically distributed.

The strategy for single step fitting of panel parts, as it is proposed within chapter 4, is to combine both absolute measures, which one could achieve by employing the introduced path correction algorithm, the panel, and the frame. The resulting combination then is equivalent to the relative measure, as it is proposed by [17]. This is resulting into an equation, which can be solved numerically, instead of a slow open loop iteration scheme, based on robot motions.

Since the robots for such panel fitting system usually holds the whole panels in his grabber while in operation, the grabber is usually quite big and hence is very limited within the motion range. That induces the need of a new robot hand calibration scheme, which is not based on dynamic pose variations during calibration. The proposed algorithm is constructed as a two-step approach, which is performing a first part of the calibration inside the Lab, before the sensor gets mounted on the grabber. The second and final step, which can then be processed with a static position in front of a calibration plate, will be performed after the sensor is mounted in its final position.

To be able to perform a single-shot calibration, the proposed algorithm utilizes the internal camera of the sensor. For most of the common laser line sensors, it is also possible to acquire the raw camera images, next to the extracted laser line coordinates. Since a camera can easily be calibrated by taking a single shot of a calibration plate, one can determine the camera's coordinate system by acquiring a single image of a well-known calibration plate in world coordinates. For the camera calibration the standard models were used, as they are described within [18] and the distortion is based on the high accurate model as presented in [19].

By having the camera's coordinate systems origin, the last thing one needs to determine is the relation between the sensor's coordinate system and the camera's coordinate system. By having the calibrated pinhole camera model, one can calculate the laser planes origin by positioning a well-defined calibration obstacle underneath the laser in various positions. Then, by knowing the relation between the camera and the laser planes origin, as well as the camera's position relative to the calibration plate, one will be able to calculate the relation from the robot's wrist to the sensor coordinate system.

The chapter detail all the steps of the implementation starting out from the lens calibration up to the necessary steps for getting the relation between the camera and the calibration plate, as well as the position of the laser frame origin.

Chapter 5:

Within this chapter the results of this thesis are discussed. This starts out with an analysis of the expected systematic error for a given surface curvature. A systematic error is within the applied mathematical model. Sometimes a mathematical model will simply get too complex if it reproduces the reality perfectly. Therefore, it is preferable to introduce some shortcomings to keep the model simple and manageable. Modelling all the factors that influence the realistic behaviour would simply be too complex. The influence of different aspects that have been left out is unmodeled systematic behaviour and can therefore be estimated. Another aspect are the purely random errors, which are induced by multiple environmental influences as well a technical limitation while recording the desired quantities from the system. Contrary to systematic errors, a random error is not describable at all for a single value; only the way it is distributed like the density function or other stochastic features can be estimated.

A systematic error, however, can be expected and estimated, since the algorithm, which was proposed in chapter 3 and 4, is based on the assumption that the surfaces contour propagates linearly. Since slight curvatures can be expected on modern car bodies, it was the purpose of the performed analysis to determine how big the induced error will be, with respect to the strength of the curvature. And since the mounting positions of panels usually do not allow a lot of movement without provoking a collision, the misplacement of panels is expected to not exceed ±10mm. That assumption is realistic, because it is a reasonable field of view for the sensor devices as well. One can expect the curvature to not change drastically within the allowed region of ±10mm. Therefore, an osculating circle at the referenced measurement point was chosen, as a sufficient approximation of the local curvature

Since the accuracy of an ordinary industrial robot can be expected to be about ±0.2mm, the goal of chapter 5 is to determine the critical limit for the surface curvature that would not influence the resulting accuracy of the application. In this section, we will carve out a correlation between the shapes' curvature and the resulting error of the model assumption.

The analysis of the systematic error concludes with a diagram which depicts the maximum error related to a given curvature radius. The diagram is based on the previously discussed maximum displacement of the object in the range of ±10mm. the diagram show that a sufficient correction quality would also be possible in areas of high curvature, like in wheel housings.

Further chapter 5 shows a set of tables containing test results of a standard implementation of the proposed path correction. To validate the quality of the calculated corrections a first test setup had been created. In this test setup the measurements have been performed on a raw production body around the door frame. The shift of the object had been simulated by a base shift of the robot and the resulting measurements have been recorded for multiple shift positions, in which each of the measures had been executed at different positions. The different tables contain the test results for the following scenarios:

- Standard setup
  (Setup like in a normal production system)
- Standard setup (not continuous)
  (Setup like in a normal production system, but robot stops in each measurement spot)

- Standard with improved feature detection
  (Uses the standard production setup, but also employs the improved feature detection, as it was proposed in chapter 3)
- Misaligned sensor positions
  (Uses slightly misaligned sensor positions, which violate the restrictions as formulated in chapter 3 for the path correction, to test out stability and error tolerance)
- Misaligned sensor positions (not continuous)
  (Uses slightly misaligned sensor positions and stops at each measurement spot, to test out stability and error tolerance)

Chapter 6:

Within this chapter one can find the conclusion of this work. It summarizes all previous chapters and emphasizes the contribution which are claimed by this work.

- Optimization and filtering of the sensor data:” A MAP estimator based on geometric Brownian motion for sample distances of laser triangulation data”
- ”Fast and robust point cloud matching based on EM-ICP prepositioning”
- ”Automatisierung von Fertigungsprozessen großvolumiger Bauteile”
- Path correction: ”An over-determined path correction algorithm for sparse dimensional measurements”
- Static laser line sensor calibration: ”A method to determine the extrinsic parameter of laser triangulation sensors, with restricted mobility”
- Panel fitting algorithm: ”A novel approach for automated car body panel fitting.”

It also provides an outlook for further research and applications of the proposed techniques in the field of collision detection and direct coupling throughout a sensor-robot interface.

Appendix A

Within appendix A the reader can find some further information about linear least square methods. It starts out with explaining the normal distribution and its central role due to the

Central Limit Theorem based on [20]. Further it derives all underlying equations with much detail and provides some insight about the underlying theoretical background of these methods. It starts out with the trivial 1-dimensional normal distributed function and derives the step by step the n-dimensional general linear case.

Further it provides some insight about the homogeneous least squares problem which was mentioned within the technical foundations in chapter 2 and shows how this problem can be solved by eigenvector decomposition or by singular value decomposition (SVD).

Appendix B

Appendix B provides insight into methods of solving nonlinear problems. Such problems might appear for multiple reasons, like nonlinearity or complex constraints. Often times an iterative algorithm searching the correct solution over multiple simple steps, choosing its descend directions based on a good heuristic, is the only way to find a solution. For such kind of iteration schemes, one usually needs to supply an error function, which calculates the difference between the results for the current parameter vector and the desired target properties. Although such functions are usually very straight forward and hence very simple to provide, it is not always preferable to solve all problems iteratively. This is due to the fact, that an iterative algorithm usually is considerably slower than a direct calculation. There is also the chance, that it might get stuck within a local minimum, or even diverge far away form the result. Such nonlinear solving methods are however the foundation to determine the result for many of the proposed methods in the previous chapters, like e.g. the path correction algorithm, or the camera calibration scheme. It covers the gradient descent algorithm in detail and gives an insight into the Guass-Newton algorithm, its derivation and all regarding formulas. Finally, the Levenberg-Marquardt algorithm, which is a combination of the two previously introduced algorithms, will be derived and explained in detail.

Appendix C

The final appendix focusses on transformations and their derivations. It starts out with explaining all the different angle notations and give a short overview about the representation of rotations as quaternions. Finally, the reader can follow the complete derivation of a rotation matrix starting out in the plane as a 2D matrix and is finally concluding to the complete rotation in tree dimensional space. The appendix also explains the construction of homogeneous transformations.

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