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3D-vision method for robust inline inspection by combining complementary shape measurement principles.

Introduction to the thesis subject

Non-contact measurement methods based on triangulation and structured light projection are widely used in industry, especially for dimensional control or inline inspection of mechanical pieces [1]. Some factors, related to the surface to be acquired, reduce the 3D measurement performances, such as specular reflections, texture variations and diffusion in non-opaque materials. In the state of the art, specific vision methods are proposed to eliminate disturbances caused by surface properties [2] [3] [4]. However, these methods are generally optimized for a limited range of disturbance causes.

Thesis objective

The objective proposed in this thesis is to study, in an industrial context, the combination of three complementary 3D optical principles in a unique instrument in order to extract robust tri-dimensional data on the objects to be acquired. The aim of this combination is to cover a wide range of measurable materials. The first principle, shape from polarization, works well with specular surfaces. The second principle, active stereovision, is suitable for uniform diffusive surfaces; and the third principle, shape from focus, is adapted for surfaces with strong texture variations.

A model will be determined using the optical properties of the system and in relation to the 3D shape reconstruction algorithms of each method. This model will have to calculate the surface shape even though some disruptive effects occurs such as specular reflection, volumetric diffusion, and textural variations. In order to ensure the metrological relevance of the experimental study, some 3D measurements will be applied on standard objects (i.e. calibrated objects) or compared with instruments using alternative technologies (interferometry, confocal microscopy …) and connected to primary standards for an accurate characterization.

Presentation of our Team, research background and partnership related to the thesis project.

Our research Team, named M2EI (Mecatronic, Energy, Electricity and Integration) is integrated in the Roberval Laboratory of the UTC (University of Technology of Compiegne). We are especially working in designing, modeling and prototyping micro-mechatronics systems and components such as actuators, sensors and communications technics. One main originality of our work is to find mechatronic solutions to enhance robustness and compactness of systems.

The M2EI research team has developed competences in contactless measurement, to acquire 3D shape in endoscopic applications [5] [6] [7]. Two thesis were conducted on this subject [8] [9] and a patent registered [10]. This endoscopic principle was also studied for integration in a µCMM (micro-Coordinate-measuring machine) in the context of a project, named MICROCOSM (Contactless *Micro Co*ordinate Me*as*uring *M*achine), funded by the Picardie Region with a collaboration with the Institut für Microtechnik of the TUBS (Technische Universität Braunschweig, in Germany) and CETIM (Technical Centre for Mechanical Industry). The contactless measurement principle is based on active stereovision by projection of structured light patterns onto the measured object. The originality of the approach lies in the digital actuator integration at the proximal end of the endoscope, which gives the functionality to switch projection and acquisition channels of the device without any movement in the distal probe [6]. In case of saturated areas caused by specular reflections, this strategy offer flexibility to get accurate measurements using the two complementary measures coming from the switch functionality. Moreover, the distal probe is compact (the voluminous optoelectronic and actuated parts of are shifted outside the measurement area thanks to the use of image guides). The integration of this 3D shape measurement technology is beneficial in a production context in terms of space optimization and robustness to electromagnetic radiations disturbances. Some remaining issues on the endoscopic system were identified such as problematic measurements due to optical disturbances occurring on the surface to be measured: specular reflections, strong texture variations, optical signal scattering… To overcome them, one solution is to select 3D measurement methods robust to these factors. This define the context of the thesis project were three distinct 3D measurement methods will be combined to reduce or eliminate the noise generated by the optical disturbances.

On previous projects, our research team has established a collaboration with the CETIM (Technical Centre for Mechanical Industry). This organism provides competences to industrial companies to improve their competitiveness; it also takes part in standardization and establishes relationships between scientific research and industry. The collaboration with the CETIM open opportunities useful for this thesis, especially the possibility to exchange with their experts on metrology and calibration, also it will let us use their standards for characterization and eventually their equipment's (multisensory CMM, white light interferometer, confocal microscope) for reference measurements.

State of the art and progress of optical methods for robust 3D shape measurement

The research topic of tri-dimensional shape measurement has a wide range of applications in areas such as industry, medicine, cultural heritage, etc [11]. In the last decade, thanks to their contactless properties, many optical methods were further researched to acquire 3D shapes, such as fringe projection [10], stereo matching [13], shape from focus [14], RGB-Depth [15], etc. Obtaining accurate 3D models by using one of these approaches is still a challenging problem, especially for irregular shapes, complex surface structures, and object materials generating disturbing optical factors such as specular reflections, texture variations, scattering…

An original approach to improve the 3D accuracy is to integrate innovative instrumental characteristics into the 3D measurement system. Integration of micro-lenses matrix before the imaging sensor leads to the emergence of plenoptics 3D-cameras [16] with possibility of range measurement on a single passive capture. There is also methods for mesuring specular or transparent materials integrating light polarizers [2]. A well-studied range of light sources allows 3D measurement and surface orientation estimation with photometric stereo methods [17]. In 3D profilometry, a cautiously design of projected patterns [18] lead to enhancement in 3D accuracy and robustness. However, each of these approaches fix a limited set of factors. The proposal of this thesis project is to integrate in a unique instrument several complementary 3D measurement principles to fix simultaneously a wider range of factors. The three selected principles are shape from polarization (SfP), active stereovision and shape from focus (SfF). With these combinations, various type of surfaces should be simultaneous measurable (surfaces with strong texture, specular surfaces, uniform diffusive surfaces…) and the robustness of the measurement enhanced.

Specific implementation plan and details

First year of the thesis

The first part of the thesis will be dedicated on studying the state of the art on the optical 3D measurement methods for inline inspection and analyzing the characteristics of the three measurement principles (SfP, SfF, active stereovision) on which this thesis rely. The combination of several of these principles will also be analyzed in the state of the art.

The second part of the year will consist on studying the "classical" optical configurations and algorithms for each of the three measurement principles. Some experimental testing will be applied to verify the validity of these configurations and algorithms. In this phase, each measurement principle will be analyzed and tested separately.

Using the results from the two previous part, the PhD student will then propose of a methodology for merging the three measurement principles, in term of instrumentation and algorithms. The student will also determine which properties, performances and characteristics can be expected due to the proposed merging. This theoretical part will be validated in the last year of the thesis by a characterization campaign.

Second year of the thesis

The first part of this second year will be oriented towards design, fabrication and programming in order to obtain a finalized 3D measurement system at the middle of the second year. In the instrumental part, the PhD student will model, design, prototype the compact measurement system equipped with actuators (needed for calibration and measurement with SfP and SfF), MEMS device for light structuring and optical elements for projecting and capturing... For this task, optical simulation software such as Zemax will be used and CAD software such as Creo. In the same time, the PhD student will develop (C, Matlab) the control software that will project the patterns, position the actuators and capture the images from the camera device.

A main task of this second year will be to implement the 3D reconstruction algorithms that combine the three measurement principles (SfP, SfF, active stereovision), in order to generate a robust acquisition system able to measure on various type of material. These algorithms will be adapted specifically to the architecture of the measurement device. Calibration algorithms will also be implemented in order to ensure the metrological validity of the 3D reconstruction process. In order to validate the device architecture, the control software and the 3D reconstruction algorithms, some testing and 3D measurement will be applied on simple surfaces (planes, spheres…) made of various materials in order to ensure the good functioning of the device and algorithms.

Third year of the thesis

The first part of the third year of the thesis will be centered on a characterization campaign. During this campaign, an experimental evaluation of the metrological performances through a comparison of the experimental and expected theoretical results will be done. The measurements will be applied to various types of objects made of different materials (metallic, plastic, glass…) and for different surface properties (texture, diffusion, reflection…). The gain obtained by each measurement principle (SfF, SfP, active stereovision) will be studied and the synergy between them analyzed. In order to ensure the metrological relevance of the experimental study, the PhD student will compare the 3D results of the measurement device with acquisitions made on instruments using alternative technologies (interferometry, confocal…) and connected to primary standards. Standards such as steps, spheres, pyramids… will also be measured and their dimensional properties controlled. The characterization campaign will be designed to validate the method proposed in the first year of the thesis and compared with the state of the art. Then, the PhD student will make some proposal of potential improvements of the method and estimate the potential impact of these improvements on performances. Finally, the last part of this third year will be dedicated to the thesis writing and defense.

Thesis schedule

<table>
<tr><th></th><th colspan="2">0 month - 3 months</th><th colspan="2">3 months - 6 months</th><th colspan="2">6 months - 9 months</th><th colspan="2">9 months - 12 months</th></tr>
<tr><td rowspan="3">Year 1</td><td colspan="5">State of the art on the optical 3D measurement methods for inline inspection. State of the art of the characteristics of the 3 measurement principles (SfP, SfF, active stereovision) for 3D reconstruction.</td><td colspan="3"></td></tr>
<tr><td></td><td colspan="6">Study of the standard optical configurations and algorithms for each of the 3 measurement principles (Sfp, SfP and active stereovision). Simple testing for each method (separately).</td><td></td></tr>
<tr><td colspan="3"></td><td colspan="5">Proposition of 1) a methodology for merging the 3 principles in a unique instrument 2) a methodology for combining the 3 principles in a unique 3D reconstruction process. Study of the advantages and characteristics of this measurement principles merging.</td></tr>
<tr><td rowspan="4">Year 2</td><td colspan="4">Instrumental design and fabrication: (adaptation of the) optical and mechanical design of the 3D instrument, actuator integration for polarizing and focusing. Fabrication and Assembly.</td><td colspan="4"></td></tr>
<tr><td colspan="4">Control programming: software implementation of image capturing, pattern projecting, actuating and data archiving.</td><td colspan="4"></td></tr>
<tr><td colspan="2"></td><td colspan="4">Algorithmic development: design and implementation of an algorithm that combine the 3 measurement principles (Sfp, SfP and active stereovision) in a unique 3D reconstruction process.</td><td colspan="2"></td></tr>
<tr><td colspan="4"></td><td colspan="4">Experimental validation of the measurement system and 3D reconstruction process : 3D shape reconstruction of samples made of various materials (metal, plastic, glass…)</td></tr>
<tr><td rowspan="3">Year 3</td><td colspan="4">Characterization campaign. Evaluation of the metrological and temporal performances of the method (with various surface properties, using standards), comparison with theoretical estimations and with state of the art.</td><td colspan="4"></td></tr>
<tr><td></td><td colspan="3">Based on the characterization campaign, validation of the methodology to enhance 3D inline inspection. Proposition of potential improvements and estimation of their impact.</td><td colspan="4"></td></tr>
<tr><td colspan="4"></td><td colspan="4">dissertation writing and defense</td></tr>
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Glossary

CAD: Computer Aided Design

CETIM : Technical Centre for Mechanical Industry

CMM : Coordinate-Measuring Machine

M2EI: Mecatronic, Energy, Electricity and Integration

MEMS: Micro-Electro-Mechanical Systems

MICROCOSM: Contactless *Micro Co*ordinate Measuring *M*achine

SfP: Shape from Polarization

SfF: Shape from Focus

TUBS: Technische Universität Braunschweig

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