Chapter 1

General Introduction

1.1 Context and Motivation

Dimensional metrology is of prime importance in the industrial and scientific domains, particularly in the field of quality control of manufactured products. In robotics too: without dimensional sensors, robots would be nothing else more than automatons, going through the same repetitive tasks again and again in a carefully controlled environment. This discipline thus requires a whole set of new sensors able to detect and characterize the position, shape and size of diverse mechanical pieces, in an ambulatory environment.

In most of the cases, dimensional measurements require a contact between the instrument and the object under study. This obviously presents some drawbacks in terms of comfort, accessibility or even security (e.g. inflammable materials).

On the contrary, other techniques allow noncontact measurements, the most widespread example probably being that of ultrasonics. Nevertheless, the limited accuracy that one can obtain with this technique, together with the inherent constraints of the method (data processing, angular aperture of the emitter, ...), affect the ultrasonics' popularity.

During the last two decades, some new techniques involving image vision appeared. Those methods involve the analysis of the properties of the luminous flux reflected or radiated by objects. To recover the geometrical structures of these objects, either to recognize or to measure their dimensions, two basic vision strategies are available.

The first strategy, known as *passive vision*, attempts to analyze the structure of the scene under ambient light. In contrast, the second, called *active vision*, aims at the reduction of the ambiguity of scene analysis by structuring the way in which images are formed. By keeping the properties of invariance in rotation and in translation of three-dimensional (3-D) objects, sensors that capitalize on active vision can resolve most of the ambiguities found with two-dimensional (2-D) imaging systems [1].

Moreover, with laser-based approaches, the 3-D information becomes relatively insensitive to background illumination and surface texture. Laser triangulation under structured lighting, on which the thesis actually lays, is an example of active vision technique.

This optomechatronic method (cf. [2] and Fig. 1.1) allows making a wide variety of dimensional, noncontact and nondestructive, measurements. Length, area, volume, diameter, curvature or 3-D model reconstruction (also called *reverse engineering*) are, among others, the possible quantities to compute with that technique.

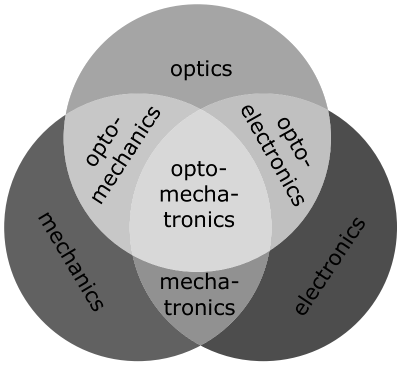

Fig. 1.1. Definition of optomechatronic technology.

1.2 Brief Description of the Method

Without entering into details at this point, the method of triangulation under structured lighting consists in (a) projecting a light pattern on an object or a surface under test, and (b) analyzing the pattern distortion on an image taken by a camera to deduce dimensional information.

The pattern can for instance be a series of noncoherent light stripes, or a laser pattern such as a circle, a square, a dot matrix or more commonly one or several lines. We can already specify that we restricted ourselves to using laser stripes (actually generated by laser planes).

The three important steps in a measurement are (a) one or more snapshots of the scene, (b) image processing to extract the characteristics of the pattern modified by the target, and (c) computation of the dimensional quantity, most usually calling upon 3-D geometry.

It is to be noted that before performing the first measurement, it is mandatory to calibrate the instrument to determine its geometrical parameters.

1.3 Philosophy of the Thesis

Even if still young, the method has been deeply studied, but almost exclusively in the case of fixed-post applications. The resolutions that one can achieve in that scope are quite impressive (about 1 μm), and the information that one can extract about the object or surface under study, quite exhaustive. The counterpart is that the instruments developed in that end are always massive and very expensive.

This thesis deals with this technique, but in an original approach: the focus is brought on the determination of specific, restricted dimensional information on objects of diverse, but *a priori* known, shapes[1] with the objective of achieving metrological performances of a reasonable level, i.e. in agreement with most of industrial needs.

Furthermore, *ambulatory instruments* are exclusively aimed, using low-cost components. By *ambulatory instruments*, one means light devices that are at least portable, or even handheld. They can thus be used on remote sites, directly where the objects stand.

Another objective is to obtain systems for which an industrial transposition to innovative instrumental products is eventually feasible. As far as we know, really few works have been done in this—yet promising—ambulatory context.

Chronologically, the thesis started with the development of a first application, involving the diameter measurement of cylindrical objects (Chapter 9). The most appropriate method to our opinion was triangulation under plane lighting, so we started bibliographical researches on the subject. The theoretical foundations of the method quickly appeared. An image processing algorithm was written, a diameter calculation method was conceived, and a calibration procedures set up; this allowed us to prove the feasibility of the method through preliminary results.

What happened next summarizes really well how the thesis was run: some theoretical aspects were improved and applied on the current application, then a new application came to mind, which emphasized new problems to solve, and so on. After multiple *application-impulsed* refinements, we eventually ended up with a solid and complete theoretical basis, exposed in the present work. It was of course applied on all the developed instruments.

Because we found it more efficient to proceed this way, the text is divided in two distinct parts, but both are strongly correlated. The first one deals with all the theoretical aspects of the method. For sake of readability, we only mention the most advanced models, and pass on the refinements that occurred during the research. The second part describes our own innovative applications, developed in the scope of the thesis. Here again, only the final results are presented, but we detail in each chapter what would have happened if the models were not so complete.

As for the innovative features of the thesis, they are mainly to be found in the whole Part II. Some original contributions—mentioned when pertinent—are also claimed in Part I.

[1]The application presented in Chapter 12 does not strictly follow this philosophy, but it will be justified later.

1.4 Outline of the Dissertation

Part I (Theory) is opened by a description of the camera model we used. Starting from a complex model, simplifications are introduced, so that we end up with a manipulable, but complete, model (Chapter 2).

The heart of the present work is probably Chapter 3, which explains in details laser triangulation under plane structured lighting. It is more particularly in this chapter that we show how it is possible to make 3-D measurements with the technique, using one or more laser planes.

Chapter 4 is devoted to the presentation of the hardware used during this work.

Image processing is the object of Chapter 5. A series of operations required during the thesis are described and illustrated on a typical image.

A perfect knowledge of the geometrical configuration of the instruments relying on structured lighting is mandatory. Chapter 6 details the calibration of the devices, useful to achieve that goal. Attention is paid to explaining how it is done in practice.

The following chapter deals with an accuracy analysis of the method (Chapter 7). Several parameters are taken into account in that end.

Part I is closed with Chapter 8, presenting a few examples of ambulatory devices using the method.

The first application described in Part II is that of diameter measurement of cylindrical objects (Chapter 9). An original, patented, method called "three-tangent method" was developed in that scope.

As an extension of this "three-tangent method," Chapter 10 deals with the diameter measurement of spherical pieces. It was also the occasion to (successfully) compare this method with an optimization method.

The next application concerns dimensional measurements in the building sector (Chapter 11). An instrument allowing the determination of various quantities such as angles, distances, ... has been developed.

The last application is the determination of the road surface microtexture. This project has been done in collaboration with the Belgian Road Research Center (Chapter 12).

We close this dissertation with some conclusions and perspectives regarding possible future works.

1.5 Personal Publications

A portion of this thesis has already been published, in the scope of scientific articles, conference proceedings or diploma dissertations under our supervision.

The present work groups and develops these publications, which are listed hereafter in chronological order. A distinction is made between four types of papers:

A paper in an international journal with referee (3 papers);

B publication in international conference proceedings (9 papers);

C publication in national conference proceedings (1 paper);

D local seminar at the university (2 papers);

E engineering diploma dissertation (5 papers).

Note that the numeration hereafter is independent from that of the bibliography. When relevant, some publications are cited in the text, and appear thus in the bibliography.

1. (E) M. Demeyere and E. Dereine, *Measurement of cylindrical pieces by laser telemetry: a feasibility study.* Eng. diploma dissertation, Université catholique de Louvain, Louvain-la-Neuve, Belgium, 2000.
2. (B) M. Demeyere, E. Dereine, and C. Eugène, "Cylindrical piece measurement through laser telemetry – application to a new forest caliper," in *Proc. of the IEEE Instrumentation and Measurement Technology Conference*, Budapest, Hungary, pp. 222–227, 21–23 May 2001.
3. (B) M. Demeyere and C. Eugène, "Measurement of cylindrical objects by laser telemetry in a robotic environment," in *Proc. of VR-Mech'01 "Workshop on Virtual Reality in Mechanical and Production Engineering / Sensory Systems in Mobile Robotics,"* Brussels, Belgium, pp. 189–193, 22–23 Nov. 2001.
4. (B) M. Demeyere and C. Eugène, "Measurement of cylindrical objects by laser telemetry in an ambulatory context," in *Proc. of the IEEE Instrumentation and Measurement Technology Conference*, Anchorage, AK, USA, pp. 1571–1576, 21–23 May 2002.
5. (E) A. Debatty and G. Gérin, *Laser triangulation under structured lighting applied to dimensional measurements in the building sector.* Supervision of an Eng. diploma dissertation, Université catholique de Louvain, Louvain-la-Neuve, Belgium, 2002.
6. (A) M. Demeyere, E. Dereine, C. Eugène, and V. Naydenov, "Measurement of cylindrical objects through laser telemetry: application to a new forest caliper," IEEE Trans. on Instrumentation and Measurement, vol. 51, pp. 645–649, 2002.

7. (B) A. Debatty, G. Gérin, M. Demeyere, and C. Eugène, "Capteur angulaire 2D à triangulation laser," in *Actes du 3ème symposium MTOI "Méthodes et Techniques Optiques pour l'Industrie,"* Saint-Aubin de Médoc, France, pp. 321–326, 18–22 Nov. 2002.

8. (B) A. Debatty, G. Gérin, M. Demeyere, and C. Eugène, "Dimensional statements by laser triangulation under structured lighting: application to the building sector," in *Proc. of the Second European Workshop Photomec2: "Photonics in Mechanical and Industrial Processes,"* Louvain-la-Neuve, Belgium, 20–21 Feb. 2003, CD-ROM.

9. (D) M. Demeyere and C. Eugène, "A camera model for industrial vision," IAP Workshop on Advanced Mechatronics Systems, Louvain-la-Neuve, Belgium, 22 Oct. 2003, poster.

10. (C) C. Eugène and M. Demeyere, "Mesures ambulatoires de grandeurs dimensionnelles par triangulation laser sous éclairage structuré," in *Actes des "Journées d'étude Optique & Vision Industrielle," par Promoptica et Bemeko*, Louvain-la-Neuve, Belgium, 20–21 Jan. 2004, CD-ROM.

11. (A) M. Demeyere and C. Eugène, "Measurement of cylindrical objects by laser telemetry: a generalization to a randomly tilted cylinder," IEEE Trans. on Instrumentation and Measurement, vol. 53, pp. 566–570, 2004.

12. (B) M. Demeyere and C. Eugène, "Determination of the road surface microtexture by laser triangulation under structured lighting: a preliminary feasibility study," in *Proc. of ODIMAP IV "4th Topical Meeting on Optoelectronic Distance/Displacement Measurements and Applications,"* Oulu, Finland, pp. 114–119, 16–18 June 2004.

13. (E) D. Rurimunzu, *Noncontact diameter determination of a sphere by laser triangulation under structured lighting.* Supervision of an Eng. postgraduate diploma dissertation, Université catholique de Louvain, Louvain-la-Neuve, Belgium, 2004.

14. (B) C. Eugène and M. Demeyere, "Ambulatory measurements of dimensional quantities by laser triangulation under structured lighting," in *Proc. of the 13th IMEKO TC-4 International Symposium "Measurements for Research and Industry Applications,"* Athens, Greece, pp. 581–586, 29 Sep.–1 Oct. 2004.

15. (D) M. Demeyere and C. Eugène, "Noncontact dimensional metrology by laser triangulation under structured lighting: development of new field instruments," seminar of the Center for Research in Mechatronics, 15 Apr. 2005.

16. (E) A. Soete, *Development of a field instrument for the combined measurement of micro– and macrotexture of road surfaces.* Supervision of an

Eng. diploma dissertation, Université catholique de Louvain, Louvain-la-Neuve, Belgium, 2005.

17. (E) C. Vasile, *Development of a field instrument for the combined measurement of micro– and macrotexture of road surfaces; part two: man-machine interface, calibration and tests.* Supervision of an Eng. post-graduate diploma dissertation, Université catholique de Louvain, Louvain-la-Neuve, Belgium, 2005.

18. (B) M. Demeyere, D. Rurimunzu, and C. Eugène, "Application of the three-tangent method to the measurement of spherical objects by laser telemetry," in *Proc. of the ISMCR'2005 "15th International Symposium on Measurement and Control in Robotics,"* Brussels, Belgium, 8–10 Nov. 2005, CD-ROM.

19. (B) A. Soete, C. Vasile, M. Demeyere, L. Goubert and C. Eugène, "Instrument de terrain pour la mesure combinée de la micro– et la macrotexture des revêtements routiers," in *Actes du 6ème symposium MTOI "Méthodes et Techniques Optiques pour l'Industrie,"* Marseille, France, 21–25 Nov. 2005.

20. (A) M. Demeyere, D. Rurimunzu, and C. Eugène, "Measurement of spherical objects by laser telemetry in an ambulatory context," accepted for publication in IEEE Trans. on Instrumentation and Measurement.

We are also the owners of the following patent: M. Demeyere, E. Dereine, C. Eugène, and V. Naydenov, "Measurement of cylindrical objects through laser telemetry," European Patent 1,305,567, 27 June 2001.

Finally, our paper no. 19 hereabove received the "Jean Ebbeni Prize," delivered by the Société Française d'Optique (French Optical Society) in November 2005 as an award for "a particularly innovative technique or application, ready or almost-ready for industry."