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Calibration of a Multi-Modal 3D Scanner

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Abstract ***–*** *Collecting dense range measurements in uncontrolled environments is a challenging problem as lighting and surfaces' texture significantly influence the quality of the measurements. Instead of concentrating on improving a specific type of range sensors, the overall quality of the sensing can also be enhanced through the development of a mechanism that combines various range sensing technologies to form a multi-modal range sensor.*

Although many different multi-modal systems have been investigated, the problem of merging datasets have hinder engineers from producing unified data. Two major approaches have been used to rectify this problem: system calibration of the multi-modal system and data fitting of all datasets into a single model, which the latter is more widely used. The lack of multi-modal system calibration approaches is due their complicated and lengthy nature, where individual calibration approaches must be applied to each subsystem and then applied between subsystems of the multi-modal range sensor.

To alleviate the problems in multi-modal system calibration, straightforward and generic guidelines for calibration are defined and applied to an in-house multi-modal system built from a laser range finder system, two active triangulation systems using structured lighting, and a stereovision system. This paper addresses the system's intra- and inter-calibration processes and presents renderings of datasets collected with the calibrated multi-modal range sensor without the use of data fitting. From these results, the potential benefits of multi-modal calibration that reduces the need of data fitting and the advantages of merging subsystem's strengths to complement other subsystem's weaknesses are put in evidence.

Keywords ***–*** *active vision, calibration, laser range finder, multi-modal scanning, range sensing, stereovision*.

I. INTRODUCTION

The introduction of smaller and portable range sensing technologies has opened the door for researchers to explore new dimensions of the world in applications like the Mars Pathfinder, which provided the first stereoscopic views of the Martian landscape in 1997 [1]. However, with scalability of technology and the reduced manufacturing costs of range sensing devices, there remains speculation of their efficiency and reliability. Even though today's consumers can purchase newly improved high-resolution cameras for a fraction of the cost of their predecessors, software implementations that handle disparity techniques have stood at a standstill with little improvement.

The introduction of active sensing techniques, such as laser range scanning and active triangulation through structured lighting has provided a different approach to range sensing which resolves conditions where classical stereovision cannot perceive depth. For example a light pattern projected on a scene can be used to detect the depth of objects in obscure and darkened environments, whereas stereovision is dependent upon the illumination of the environment and the texturing of the scene. Laser range sensors, which lately have been reducing in power consumption and size, have been the forefront in depth sensing providing far more accurate depth estimation than previous techniques. However, the greatest drawback of most of the current active sensors is their ability to detect depth only over a single plane or a sparse detection grid of a non-reflective object within close proximity of the scanner. This implies the repetitive process of moving the active scanner to various and strategic poses to complete a full scene scan, unlike stereovision where one sampling is sufficient.

With each technology providing advantages and drawbacks in their respective domains, a promising solution consists of the combination of the efforts of various range sensing techniques to create a multi-modal or a joint range sensing technique that would provide different depth perspectives of a scene from a common viewpoint.

Although, this approach in providing optimal depth sensing data is very promising, the question of registration between range sensors remains a critical issue to ensure consistency between the measurements. In this paper, the objective is to propose an approach that achieves calibration within multi-modal scanning systems. Results are validated from measurements generated by a prototype of a multi-modal range sensor that is described.

II. BACKGROUND AND CONCEPTS

The idea of using two or more range sensing systems is not a new concept to the field of range sensing. Although the idealism is to perfect the range sensing technique of an individual system, such that the complexity of calibration between subsystems and the introduction of additional errors are avoided, the concept of a different perspective is becoming more popular in the field. The term "multi-modal" has not been widely used, however different implementations of multi-modal systems have been built to integrate range sensing datasets in hopes to improve modeling of a scanned region.

From a high level view, multi-modal systems can be defined by their multiple and diverse modes of range sensors used to perceive a scenery. Systems that use multiple yet identical modes are not considered multi-modal since only a single mode is used. With this mind, the coined definitions of active and passive range sensing [2,3] can be extended for the purpose of multi-modal systems into homogeneous sensing and heterogeneous sensing. A homogeneous sensing system is defined as the application of range sensing technologies that are built from all active or all passive subsystems. Likewise, heterogeneous sensing systems use both active and passive subsystems in tandem.

A successful example of a multi-modal homogeneous range sensing system is the application of two active range sensing systems: a laser range finder and a sonar/acoustic sensing system as proposed in [4] and [5]. With these two methods, the laser range finder and sonar system sample separately without knowledge of each other's extrinsic locations. Once the individual scans have been completed by each subsystem the two datasets are fused together to provide a single map of the environment. The success of this multi-modal system is dependent upon the environment the system is placed in. For example if the environment is simply a maze where walls are the only objects, the system performs admirably. However in a complex environment where there are objects of varying height, there is no mechanism that correlates the measurement of what the laser range finder perceived with that of the sonar system.

The common example of a multi-modal heterogeneous range sensing system is that of the omnidirectional stereo and a rotating laser range finder system, proposed by Miura *et al*. [6]. In these systems, a passive sensor, omnidirectional stereo, is merged with the active laser range finder. The complexity of merging the datasets of both range sensing technologies is clearly defined by Miura *et al*., which unlike [4] and [5] outline the dilemma of different possible perceptions of an object. As a solution, Miura *et al*. propose the use of probabilistic grids to aid in classifying each subsystem based upon their strengths, weaknesses and limitations, which are all important factors when merging datasets [6].

With these two various approaches and all systems considered, a different heterogeneous sensor can be defined, which uses three active range sensing systems (one laser range finder system and two active triangulation systems) and one passive range sensing system (stereovision system).

Although there are many different approaches to system calibration for both intrinsic and extrinsic properties, the classical technique of Tsai's camera calibration model for stereovision calibration [7], a refined version of Chen and Kak's structured lighting active triangulation subsystem calibration [8], and Pless and Zhang's closed-form solution for camera to laser range finder relationship [9] are applied.

Chen and Kak's model of active triangulation system calibration could be replaced by other well known calibration methods such as noticed by Trucco and Fisher [10]. However Chen and Kak provide the interesting idea of using a simple calibration target which relies upon the movement of a robot end-effector carrying the laser projector and camera. The use of two-dimensional projectivity theorems to derive a transformation matrix that converts detected structured light emitted on defined edges in the world space provides a simpler calibration approach that can be easily used in automated calibration.

The closed form solution defined by Pless and Zhang for the purpose of relating a laser range finder and camera system [9] is appropriate for inter-subsystem calibration between the laser range finder and the stereo system. Instead of using a planar pattern placed in different poses from the camera and laser range finder, the same calibration target proposed by Chen and Kak is exercised such that the stereo system can detect the defined edges of a known object in world space.

III. PROPOSED APPROACH

The proposed multi-modal range sensing system consists of four subsystems using three range sensing techniques. The first subsystem is a laser range finder, which provides two-dimensional data along a scan-line marked by a visible red line projected on the scene. The second subsystem is a stereovision system built from two CCD cameras mounted in close proximity to the laser range finder. The third and fourth subsystems are active triangulation systems that use the left and right stereovision cameras independently to detect the projected structured light emitted from the laser range finder.

Three major objectives are defined for constructing a multi-modal system that can provide effective range sensing data for three-dimensional reconstruction:

Objective 1: Define a multi-modal infrastructure and strategically place sensing systems where correlation between systems can be achieved. A quick assessment of the range sensing technologies indicates that in active triangulation the cameras must be placed in non-coplanar position to the laser range finder structured light. Active triangulation is highly dependent upon the location of the laser pattern detected in the image. If the cameras were placed co-planar to the projected line strip, the detected line in the system would remain fixed regardless of the depth of the object in the path of the structured light. This would make it extremely difficult for the active triangulation system to extract range data. For the stereovision system, the cameras must have an appropriate baseline, selected such that objects are visible from both cameras, and disparity is detectable between the acquired images. Figure 1 shows the selected configuration.

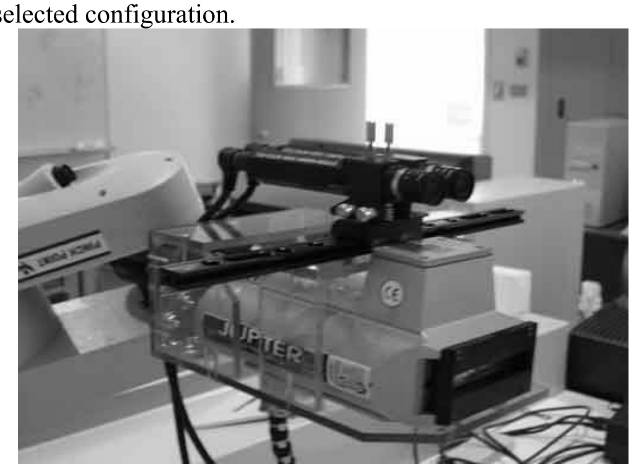

Fig. 1: Multi-modal chassis attached to the robot end effector.

Objective 2: Define a common calibration mechanism that is cost-effective, uses minimal workspace and can be used in auto-calibration. This second step of the design of a multi-modal system defines a calibration mechanism that may be used for each subsystem. The classical Tsai's camera calibration technique [7] is used to calibrate the stereo subsystem. A modified version of Chen and Kak's structured light calibration [8] for active triangulation systems is developed for the multi-modal purposes.

Objective 3: *Determine a global frame of reference with respect to which all three-dimensional datasets are defined.* This objective can be achieved intuitively, especially if the majority of the sensing systems have a common reference point. For the designed multi-modal range sensor, three of the four range sensors can conveniently provide depth information from the laser projector optical center. The flexible active triangulation systems can report depth information from any frame of reference. Since active triangulation is highly dependent on the visible structured light, it is appropriate to directly represent active triangulation depth from the structured light projector frame of reference. This frame of reference is also the laser range finder frame of reference, eliminating the need of inter-subsystem calibration between laser range finder and active triangulation subsystems.

Stereovision on the other hand provides depth information with respects to a single camera optical center. Therefore, it is necessary to build an additional calibration mechanism to translate stereovision depth to the laser range finder perspectives. This is accomplished by using Pless and Zhang's closed form solution for extrinsic calibration mechanisms [9].

IV. MULTI-MODAL CALIBRATION

The largest difficulty of using a multi-modal system is the organization required to calibrate each subsystem and interoperating subsystems. For the scenario of using a laser range finder, stereovision, and two active triangulation systems, calibration can seem more problematic. However, with a systematic approach and the reduction of transformations, it is possible to provide a resilient automated calibration mechanism. The approaches used for each subsystem calibration are now detailed.

A. Stereovision Subsystem Calibration

Stereovision calibration has been researched extensively and for the purposes of subsystem calibration the classical Tsai's camera calibration technique [7] is used to calibrate individual cameras and determine extrinsic and intrinsic parameters between the pair of camera reference frames.

B. Laser range Finder Subsystem Calibration

The laser range finder subsystem ideally comes with its own internal calibration mechanism that self-calibrates the device or contain static calibration parameters. The Jupiter laser range finder used in the experimental setup has a fixed calibration made by the manufacturer.

C. Active Triangulation Subsystem Calibration

Since stereovision and the structured lighting from the laser range finder are available, this feature is exploited to create two active triangulation subsystems, one for each CCD camera. The proposed calibration mechanism is based upon Chen and Kak's active triangulation calibration technique [8] where a recovery conversion matrix can be built from a minimal set of four known points on the surface of a given object:

$$\rho \begin{bmatrix} x_i \\ y_i \\ z_i \\ 1 \end{bmatrix} = \begin{bmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \\ t_{41} & t_{42} & 1 \end{bmatrix} \begin{bmatrix} u_i \\ v_i \\ 1 \end{bmatrix} \quad (1)$$

where the three-dimensional world depth points are represented as $[x_i, y_i, z_i]$, $[u_i, v_i]$ are perceived structured light pattern points from the image plane, t_{MN} are the conversion matrix coefficients, and ρ is a variable associated with the scaling factor. Eq. (1) is simplified as:

$$\rho \begin{bmatrix} x_i \\ y_i \\ z_i \\ 1 \end{bmatrix} = \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix} \cdot U \quad (2)$$

When ρ is normalized, it results in:

$$\begin{aligned} x_i &= T_1 \cdot U \;/\; T_4 \cdot U \\ y_i &= T_2 \cdot U \;/\; T_4 \cdot U \\ z_i &= T_3 \cdot U \;/\; T_4 \cdot U \end{aligned} \quad (3)$$

that can be rewritten as:

$$\begin{aligned} T_1 \cdot U - x_i\, T_4 \cdot U &= 0 \\ T_2 \cdot U - y_i\, T_4 \cdot U &= 0 \\ T_3 \cdot U - z_i\, T_4 \cdot U &= 0 \end{aligned} \quad (4)$$

To determine the transformation matrix (T_1, T_2, T_3, and T_4), Chen and Kak proposed an acquisition process that requires that the projected structured light pattern fall on known points. This acquisition process, which is easily used for automation, requires that a simple object, the calibration target, be placed in the path of the structured light such that its edges would form discontinuities in the structured light and would be detectable by the camera system. In addition, the edges of the calibration target would be known and characterized by the intersection of planes defined in the world coordinate frame and substituted in eq. (4). The active triangulation system is then finally positioned at different locations by movement of the robotic arm away from the calibration target and edges are extracted from the image such that U in eq. (4) is sampled such that a minimal set of four unique samples is acquired.

An adaptation of Chen and Kak's automation process is proposed that takes advantage of depth data that is perceived by the laser range finder. The calibration target is a triangular shaped piece of cardboard with its face placed directly in front of the path of the striped structured light, as shown in Figure 2. Instead of determining the geometric intersecting planes within the world coordinate frame, these inaccurate manual measurements are replaced with samplings from the laser range finder. By extracting the edge points that the structured light plane forms with the calibration target, both the laser range finder and the camera systems can easily detect the discontinuities in the line scan. As a result, this adaptive method of calibration requires no a priori knowledge of the calibration target.

By expanding eq. (1), a set of linear equations based upon the number of sampled points used in calibration is generated. The expansion of the first row gives:

$$\begin{gathered} t_{11}\times u_1 + t_{12}\times v_1 + t_{13} = x_1 \\ t_{11}\times u_2 + t_{12}\times v_2 + t_{13} = x_2 \\ \ldots\ldots \\ t_{11}\times u_N + t_{12}\times v_N + t_{13} = x_N \end{gathered} \tag{5}$$

By substituting eq. (5) and other expanded rows into eq. (4), the end matrix is formed such that:

$$Ax = b \tag{6}$$

where:

$$A=\begin{bmatrix} u_1 & v_1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & -u_1\times x_1 & -v_1\times x_1 \\ u_2 & v_2 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & -u_2\times x_2 & -v_2\times x_2 \\ & & & & & \ldots\ldots & & & & & \\ u_N & v_N & 1 & 0 & 0 & 0 & 0 & 0 & 0 & -u_N\times x_N & -v_N\times x_N \\ 0 & 0 & 0 & u_1 & v_1 & 1 & 0 & 0 & 0 & -u_1\times y_1 & -v_1\times y_1 \\ 0 & 0 & 0 & u_2 & v_2 & 1 & 0 & 0 & 0 & -u_2\times y_2 & -v_2\times y_2 \\ & & & & & \ldots\ldots & & & & & \\ 0 & 0 & 0 & u_N & v_N & 1 & 0 & 0 & 0 & -u_N\times y_N & -v_N\times y_N \\ 0 & 0 & 0 & 0 & 0 & 0 & u_1 & v_1 & 1 & -u_1\times z_1 & -v_1\times z_1 \\ 0 & 0 & 0 & 0 & 0 & 0 & u_2 & v_2 & 1 & -u_2\times z_2 & -v_2\times z_2 \\ & & & & & \ldots\ldots & & & & & \\ 0 & 0 & 0 & 0 & 0 & 0 & u_N & v_N & 1 & -u_N\times z_N & -v_N\times z_N \end{bmatrix}$$

$$x=\begin{bmatrix} t_{11} \\ t_{12} \\ t_{13} \\ t_{21} \\ t_{22} \\ t_{23} \\ t_{31} \\ t_{32} \\ t_{33} \\ t_{41} \\ t_{42} \end{bmatrix} \qquad b=\begin{bmatrix} x_1 \\ x_2 \\ \ldots\ldots \\ x_N \\ y_1 \\ y_2 \\ \ldots\ldots \\ y_N \\ \ldots\ldots \\ z_1 \\ z_2 \\ z_N \end{bmatrix}$$

which can be solved for x.

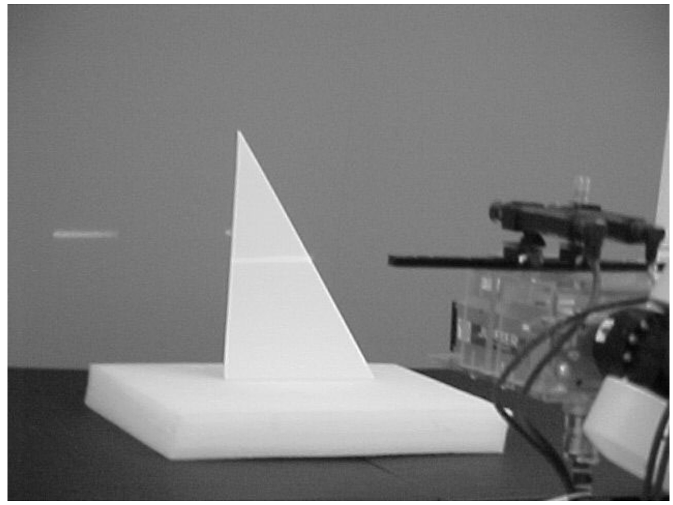

Fig. 2: Multi-modal system calibration.

These modifications to Chen and Kak's approach not only reduce human error but also simplify the procedure by eliminating the need to determine the complicated intersecting planes defining the edges of the calibration target. Full advantage is then taken of the multi-modality of the sensory system, even during the calibration phase. In addition, this adaptation holds the ability to estimate three-dimensional coordinates with respects to the laser range finder reference frame, given that the same calibration target is used between the laser range finder and active triangulation systems.

D. Stereovision and Laser Range Finder Inter-Calibration

Only one subsystem-to-subsystem calibration is required to complete the design of the proposed multi-modal system, that is a calibration between the stereovision and the laser range finder reference frames. A calibration mechanism is proposed which is similar to that used for active triangulation calibration and which utilizes the same calibration target.

The following standard transformation equation allows to relate the stereovision reference frame to the laser range finder reference frame as long as their extrinsic properties remain unchanged, which is ensured by the fixed assembly on the robot's end effector. A three-dimensional coordinate observed by the laser range finder and the stereovision subsystem is denoted respectively by P_{LRF} and P_{SV}. The stereovision system is related to the laser range finder by a rotational matrix and a translation vector denoted by R_{S2L} and T, such that.

$$P_{LRF} = R_{S2L}P_{SV} - T \tag{7}$$

Since the laser range finder depth perception points are within the field of view of the stereovision system, the equation to relate the laser range finder to the stereovision system is rewritten.

$$P_{SV} = R_{L2S}(P_{LRF} + T) \tag{8}$$

where $R_{L2S} = R_{S2L}^{-1}$.

Given the fact that the laser range finder scans a single line, the laser range finder depth values are two-dimensional such that all points are found along a common plane, Y=0. Therefore all sampled depth values can be denoted as $P_{LRF} = [X, Z, 1]^T$ in homogeneous coordinates. Using a compact notation, eq. (8) becomes:

$$P_{SV} = R_{L2S} \begin{pmatrix} 1 & 0 & \\ 0 & 0 & T \\ 0 & 1 & \end{pmatrix} P_{LRF} \qquad (9)$$

where $T = [t_X, t_Y, t_Z]^T$ and R_{L2S} is a (3×3) rotational matrix.

Solving eq. (9) is then simplified to the identification of the calibration matrix M.

$$P_{SV} = M \cdot P_{LRF} \qquad (10)$$

The same procedure for extracting correlating points in active triangulation is used to calibrate the stereovision and laser range finder subsystem. By determining the structured light discontinuities within a single foreground (made by the calibration target) and background scene and with sufficient correlating sample points, which requires a minimum of three samples, the relationship defined in eq. (10) can be determined. This calibration matrix, M, is then inverted and applied to translate stereovision three-dimensional points into the laser range finder reference frame.

Unlike Pless and Zhang's approach for camera to laser range finder calibration, which uses a linear closed-form solution and a regressive non-linear optimization approach to correlate between the camera frame of reference and laser range finder [9], only the linear closed-form solution is required by taking advantage of the structured light. The complexity of stereovision and laser range finder subsystem calibration is reduced when the structured light is projected on the scene. To correlate points between the laser range finder subsystem and the stereovision subsystem, the same approach as discussed in active triangulation subsystem calibration is used where a triangular face cardboard is placed in the direct path of the laser range finder structured light and the stereovision system. The laser range finder and the stereovision system detect the discontinuities in the structured light pattern. The discontinuities in the image planes help generate a three-dimensional point from the stereovision reference frame, which is then used to correlate with the laser range finder reference frame.

V. CALIBRATION OVERVIEW

The entire calibration process of each multi-modal system can be completed within a single instance. The calibration target used for this multi-modal system is the combination of the targets from Tsai camera calibration approach with Chen and Kak's active triangulation approach. With regards to active triangulation calibration and stereovision to laser range finder calibration, they both use the same mechanism to calibrate. This permits the reuse of calibration samples for either system. Stereovision calibration can also be integrated within the same calibration space by placing a calibration pattern on the same target used by the active triangulation. The only requirement is to have the multi-modal system capture sampling points after different world locations. Thus a single calibration target can completely calibrate the entire multi-modal system. The following chart characterizes the multi-modal system that is currently implemented, the subsystems used, the equipment, the intra-system and the inter-system calibration required.

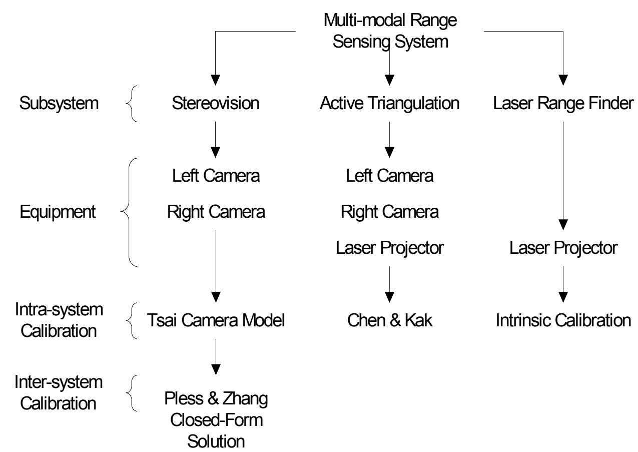

Fig. 3: Multi-modal system's structural overview.

VI. EXPERIMENTAL RESULTS

To implement the multi-modal range sensor, a chassis has been constructed to anchor the laser range finder with the stereovision camera such that the extrinsic parameters between the subsystems remain fixed, regardless of the orientation and position of the robot end-effector that is used to move the multi-modal sensing device [11]. Among the integrated sensors subsystems, the Servo-Robot Inc. Jupiter laser line scanner with its controller, the Cami-Box, performs as the laser range finder. To minimize the weight on the end-effector, the VRex CAM3000c system with two Sony XC-999 CCD cameras was selected as the stereovision system. This system is coupled to a Matrox Orion video card with support from the Matrox Image Library (MIL) and Open Computer Vision Library (OpenCV) to perform the basic video frame-grabbing and the necessary image processing.

Sequences of images were taken by the multi-modal range sensor on various objects following intra- and inter-calibration of the system using the proposed approach. Figure 4 presents experimental results for a rectilinear vase whose rim is slightly tilted. Each dataset from both active triangulation systems (left and right), the laser range finder and the stereovision subsystem have been transformed such that the views are seen from the same perspective. Scans were performed at a granularity of 1 mm between successive scan lines of the laser range finder.

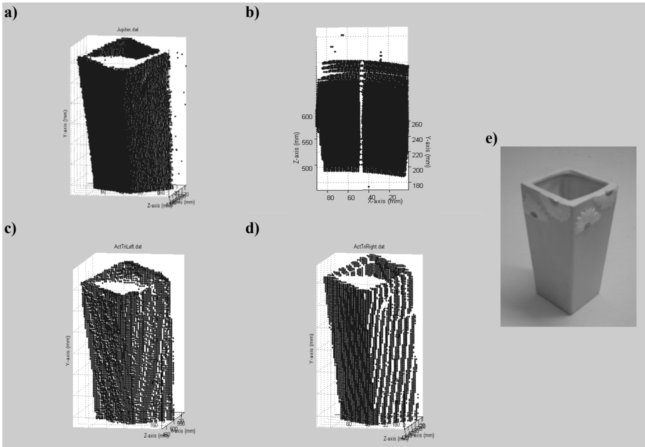

Fig. 4: Point cloud rendering of a rectilinear vase scanned with: a) laser range finder, b) stereovision, c) active triangulation using left camera, d) active triangulation using right camera, e) picture of the vase.

From visual inspection of the datasets, the difference in precision and accuracy provided by each system is noticeable. For example, the scans resulting from the stereovision system identify the vase but do not clearly distinguish that the vase is positioned such that its' corner edge is the closest to the scanner. The dependency on textures and important limitations observed on the Birchfield *et al*. approach [12] for dense disparity estimation included in the OpenCV library that is used for 3D reconstruction explain these inaccuracies.

On the other hand, the results obtained after calibration from both active triangulation subsystems, consistently provide datasets similar to each other and to the high accuracy measurements of the laser range finder. These results demonstrate the validity and the accuracy that can be achieved with the proposed calibration scheme.

Experimentation conducted during the development of the multi-modal sensor provided an opportunity to observe the sensitivity of the various modes of acquisition. For example, stereovision revealed to be highly dependent upon an illuminated environment, which ensures that the scan target is detected and distinguished from other foreground and background objects. Active triangulation appeared to be dependent upon the ability to extract the structured light pattern emitted onto the scene. A dimmed light setting was found to be appropriate for this range sensor to perform. These two contrasting environmental conditions provide a supplementary challenge if simultaneous calibration is desired. For the purpose of development, the proposed multi-modal range sensor system was placed in an accommodating environment where each subsystem can fully operate and can correlate features between each other. Lighting is adjusted such that stereovision can easily differentiate textured objects and where the active triangulation and laser range finder system accurately extracts structured light pattern without over-saturated lighting.

VII. CONCLUSION

An original calibration scheme has been introduced to determine the intra- and inter-calibration parameters for a multi-modal range sensing device that advantageously combines the respective strengths of an active laser range finder, a dual structured lighting system and a dense stereovision approach. Experimental results demonstrated the validity of the approach and the accuracy that can be achieved. This work also leaded to the development of generic guidelines for the design of multi-modal sensing systems.

Experimentation put in evidence the strict requirements that must be applied to ensure that calibration is performed in suitable conditions. Using the defined multi-modal calibration process with the proposed multi-modal range sensor, applications that were traditionally dependent upon single mode range sensors can be easily replaced by multi-modal range sensors that provide supportive results, reducing occlusions, and improving the accuracy of the entire system.

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