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Procedia CIRP 12 (2013) 222 – 227
www.elsevier.com/locate/procedia

8th CIRP Conference on Intelligent Computation in Manufacturing Engineering

Low cost scanning device application for footwear industry

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Abstract

Notwithstanding laser scanning technology is a mature technology used in widening application fields, a variety of barriers hinds its integration in robotized production lines. To face well know problems, as high-costs and not customizable solutions among others, the authors have developed a new family of laser scanning devices based on off the shelves and low cost hardware components and on a modular design that allow the customization of the device according to the specific application requirements. High accuracy is guaranteed through a computationally efficient non-parametric calibration procedure. Keeping limited the overall cost of the solution provided while increasing in general the sensing capabilities of an Industrial Robot (IR) and in particular the autonomous recognition of position, orientation and furthermore shape and geometrical features of objects within the robotic workspace, can boost the penetration of IRs in typical traditional industrial sectors where SMEs productive scenario is mainly characterized by manual fabrication processes, high product variability, small batches and little capital investments. High added value footwear industry is a paradigmatic example where hard automation is limited from one side by high variability of products and huge request of autonomous adaptation to cope with different loosely structured fabrication processes and from the other side by a low propensity towards high capital investment that make difficult the penetration of industrial robots. Within the framework of the European Project ROBOFOOT (EU-FP7-SMP), authors have conceived and developed a new family of low cost modular and reconfigurable laser scanners and successfully applied in the footwear fabrication scenario. Various operations should be improved by actual measure of the shoe being manufactured, and among the others, the identification of the relative positioning between the last (the plastic element on top of which is built the shoe) and the gripping device is extremely critical because it is still performed manually. Positioning errors in this phase are critical since all robot part-programs depend on the correct alignment of the last with the robot end-effector. To face this problem, a procedure, based on the Iterative Closest Points (ICP) optimization method, has been developed and integrated on board of the laser scanning device that directly communicates with the robot controller to adapt and autonomously correct the part-program to align the tool nominal path with the actual shoe being manufactured. Efficacy of the proposed methods has been proved by measuring the interaction forces between the tool and the last handled by a robot during different technological operations (roughing, polishing etc) typical of the shoe fabrication cycle.

Selection and peer review under responsibility of Professor Roberto Teti

Keyword: Automation; Open architecture; Opto-electronic.

1. Introduction

Vision systems based on laser scanning techniques is a mature technology used in widening application fields [1-3], and off-the-shelves devices already integrates state-of-the-art design and calibration methodologies. However, actual devices are characterized by some limitations: (i) they are closed and stand-alone solutions with fixed number of cameras, laser edges, and predefined workspace shape; (ii) they are extremely costly. These limitations do not allow the adoption of laser scanner devices in small batch production lines, and looking for a solution is a challenging task with potential relapses in many applications. In fact small-batches characterize mass customization that is the consolidate trend also for traditional industry trying to follow customers' unique demand [4]. Key-factor in design low-cost and modular laser scanning devices is the calibration methodology that has to guarantee high accuracy despite low-cost mechanic, electronics, software and optics. Under this assumption, implicit

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Selection and peer review under responsibility of Professor Roberto Teti
doi:10.1016/j.procir.2013.09.039

calibration methods [5-6] seem to be unsuitable because of their inner complexity when laser scanning system is composed by more cameras and/or laser edges, and due to the correlation among device's and components' accuracy. Extrinsic calibration models are more appealing even if few examples outside mobile-robotics are available [7-8].

Low cost and modular laser scanning system should be extremely useful in shoe-production applications. In fact, among others, footwear scenario is a challenging industry where these kinds of devices should boost the penetration of automation and IRs. In fact, operations are still basically manual and actual research activities are up to now mainly focused on the investigation of computer-aided tools for shoes-design phase and the operation planning [9-11], although, the automation-trap consists on the high level of uncertainties (in terms of loosely structured environments) of various shoe production phases. In fact actual shoe is usually significantly different from CAD models, because of tissue deformation, glues and other components used in shoe production introduce high variability in the shoe shape. In addition, the last - the plastic element on top of which is built the shoe – often is different from CAD model and, in addition, the shoe upper is not mounted on the last in a repetitive way. At the state-of-the-art there are no CAM solutions that allow foreseeing the evolution of the shoe-geometry during production. Thus, measure of the single-shoe or of the single-last in the production system seems, by now, the only solution in order to allow the introduction of robot inside the production line, paving the path for autonomous adaptation of the nominal robot part program to the actual geometrical characteristics of the shoe being manufactured

The paper presents a new framework for the design of new families of laser scanning, based on modular design, allowing the use of low-cost components, and customizable on the specific application's requirements. The paper reports an application example in the footwear industry. Thanks to the modularity of the presented device, the authors have solved the problem of the measure of the actual coupling between the last and the gripping device that is usually characterized by a poor accuracy. An automatic procedure that modifies off-line the robot part-program allows higher accuracy in the tool path planning so reducing the unwonted-constraint forces when the shoe is brought in contact with tools by a robot. Efficacy is proven by experiments.

2. Low Cost Scanning Device

2.1. ITIA laser scanning framework

Following the considerations reported in the introduction, the mandatory requirements for new laser scanning systems should be: (i) modularity, (ii) flexibility, (iii) scalability, and (iv) low-cost. These requirements are extremely different from the characteristics of actual standard solutions which are typically high-quality monolithic products characterized by high cost. As a consequence, the use of these typologies of 3D laser scanning devices is limited in niche sectors.

To overcome these limitations and meet the above mentioned requirements the proposed approach consists of the following phases:

- Identification of a set of basic laser scanning modules (LSMs) each consisting of a camera, a laser edge and one or more auxiliary axes to move the camera and/or the laser edge
- Identification of the optimum number and configuration of basic LSMs and identification of their relative positions to tackle the application requirements;
- Identification for each basic LSM of the cheaper off-the-shelves components that guarantee the nominal required accuracy
- Design of the laser scanning system (LSS) as a combination of different basic LSMs.

As a consequence the LSS calibration can be split in two phases:

- Calibration of each basic LSM;
- Mutual calibration of different LSMs by back-projecting a common reference frame.

According to this approach the LSS can be conceived, designed and tailored according to the requirements of the specific application drastically reducing the cost of the device itself without compromising the overall quality.

Accuracy of the LSS depends on the accuracy achieved through the calibration procedure of each LSM and on the precision characterizing the mutual calibration of different LSMs composing the LSS. Since the complexity of nominal models of such system, non-parametric calibration methodologies have been implemented.

However these calibration strategies need a huge quantity of data to be elaborated, shifting the problem from optic/mechanic accuracy to computational efficiency.

Furthermore, mechanical modularity requires software modularity and versatility in order to allow the calibration of different systems with different procedures and techniques.

2.2. Laser scanner module (LSM) calibration

As anticipated a volumetric calibration (not based on the characteristic parameters of the instrument) of each

LSM has been studied and implemented. By means of a calibration station analytical functions (3°/4° polynomial series) map the 2D points acquired by the camera to the 3D reference frame of the device.

The calibration station designed and implemented to set up the calibration procedure is composed of a pattern that identifies different remarkable points and an axis orthogonal to the pattern.

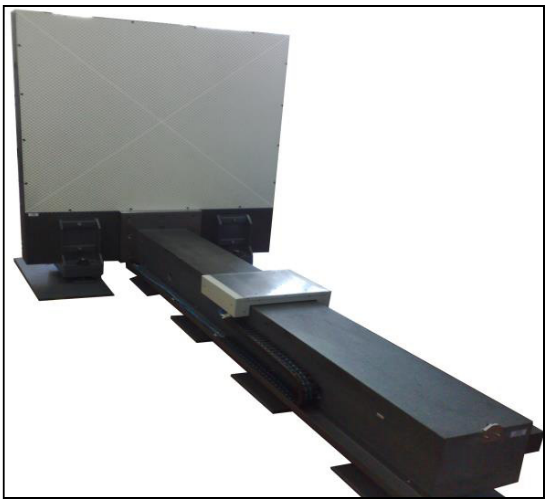


Fig. 1. Calibration station

The whole station has been made of stone in order to ensure the thermal stability and the pattern has been made of ceramic coating. The stone coupled with the ceramic coating have a maximum a variation of 0.004mm in the range between 18 and 28 °C.

The first step of the calibration procedure consists of mapping the space through non-linear regression of a multitude known points (up to 50.000.000 in a scanner with a high-resolution cam). Then the false positives are filtered through numerous cross-checks. Finally the polynomial coefficients which locally approximate the trend of 3D coordinates are identified. The management of this huge quantity of data has been solved by designing scalable multi-CPU cluster solution (GNU/Linux O.S. Based).

2.3. Laser scanning system (LSS) calibration

Being the LSS composed of different LMSs the complete 3D object digitalization is obtained composing data (clouds of points) coming from various acquisitions done by the different basic LSMs. An available and easy solution to perform manually this operation could be the use of specific software tools (like Geomagic, Meshlab etc.). However this approach is characterized by several drawbacks:

- it needs skilled operators with a specific competence on proprietary software;
- high number of acquisitions are usually required and the acquired clouds of points must overlap each other for a sufficient portion;
- using such software tools clouds of point registration can be characterized by low reliability and minimization might not converge.

To overcome these limitations, passive markers can be integrated for referencing different points and implementing a semiautomatic reconstruction procedure; this solution certainly improves the system reliability but does not allow complete process automation. In fact, the use of software tools for cloud of points manipulation cannot be avoided and the markers must always be carefully placed within the working volume of each LMS.

Furthermore both manual and semiautomatic procedure are time consuming.

In order to overcome the highlighted inefficiencies, an automatic calibration procedure was designed and implemented. This self-calibration procedure allows the back-projection of points in a single reference system endowing a native self-alignment of different clouds of points acquired. The calibration procedure is based on the use of an artifact that identifies a series of significant and a priori known geometrical points and features. For each acquisition, two correspondent set of points can be defined:

- {psi} remarkable points in the LMS coordinate frame, with i = 1 .. N
- {pbi} remarkable points in the base coordinate frame, with i = 1 .. N

The relationship between the two set of points is as follows:

$$pb_i = \overline{R} \cdot ps_i + \overline{T} + \overline{V_i} \quad (1)$$

where R is a 3x3 standard orthonormal rotation matrix, T is a 3x1 translation vector and V_i is the “noise” vector (i.e. the fitting surface could be affected by a minimum error). The optimal solution for *[R, T]* transformation allow the mapping of set of points $\{ps_i\}$ onto $\{pb_i\}$ and the scanning point back-projection onto the base coordinate system. The solution typically requires a least squares error minimization criterion given by:

$$\Sigma^2 = \sum \left\| pb_i - \overline{R} \cdot ps_i - \overline{T} \right\|^2 \quad (2)$$

2.3.1. Clouds of points alignment

Denoting respectively $\overline{ps}$ and $\overline{pb}$ the centroids of the sets of points $\{ps_i\}$ and $\{pb_i\}$ it is possible to write:

$$pbc_i = pb_i - \overline{pb} = pb_i - \frac{\sum pb_i}{N} \quad (3)$$

$$psc_i = ps_i - \overline{ps} = ps_i - \frac{\sum ps_i}{N} \quad (4)$$

Similarly to eq (2), let denote Σ as

$$\Sigma^2 = \sum \left\| pbc_i - \overline{R} \cdot psc_i \right\|^2 \quad (5)$$

$$\Sigma^2 = \sum \left(pbc_i^T \cdot pbc_i + psc_i^T \cdot psc_i - 2 \cdot pbc_i^T \cdot \overline{R} \cdot psc_i \right) \quad (6)$$

Finally, denote the correlation matrix *K* as

$$K = \sum psc_i \cdot pbc_{i\ i}^T \,. \quad (7)$$

From algebra theory, it is possible to assert that maximizing

$$tr\left(\overline{R} \cdot K\right) \quad (8)$$

is equivalent to the equation (2) minimization. The unknown rotation matrix *R* that maximizes the trace can be calculated by the singular value decomposition of correlation matrix *K*.

$$K = U \cdot \Sigma \cdot V^T \text{, and } \overline{R} = U \cdot V^T \quad (9)$$

Thus, the translation vector is estimated by:

$$\overline{T} = \overline{p}b - \overline{R} \cdot \overline{p}s \,. \quad (10)$$

3. Low Cost Scanning Station for the Footwear Scenario

3.1. Overall description of the footwear scenario

In traditional footwear manufacturing, the operator holds the last and performs various operations (as roughing, finishing, gluing etc.). Handling the last with the robot needs the coupling of the last with a suitable gripping device, and the most common solution consists of adding a metal piece on the upper part of the last.

Fig. 2. Last coupled with gripping device

Positioning of the gripping device on top of the last is usually performed manually so the accuracy can't be guaranteed and the identification of the relative position between the last and the gripping device is mandatory to adapt the nominal tool path to the actual geometry. To measure this misalignment, the authors propose the use of a custom laser scanning system.

3.2. Design and mechanical description

For the acquisition of the last coupled with a gripping device the requirements are: working volume equal to 300x300x600 mm^3, accuracy equal or less than 0.1 mm, and acquisition time equal or less than 30 sec.

To reach the final configuration different conceptual designs of *LSMs* and *LSS* have been developed and different tests for the identification of suitable components (laser, optic, camera etc.) have been performed. The optimal solution selected consists of:

- 4 *LSMs,* each *LSM* is provided by one camera (752 x 480 pixels) and a laser emitter (Class 3R)
- 1 linear axis that moves the target (last coupled with the gripping device)

The target motion and the acquisition are synchronized and managed by the same PC embedded.

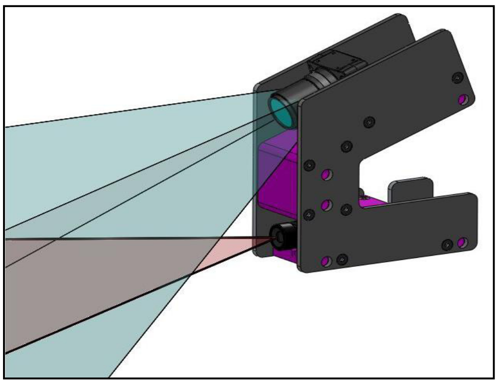
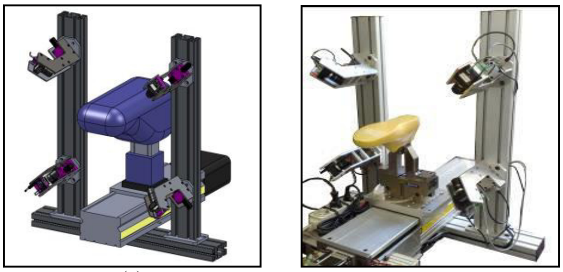


Fig. 3. Linear laser scanner module



(a) (b)

Fig. 4. (a) ITIA LSS system cad model; (b) ITIA LSS system

It is worth to underline that according to the design choices the whole acquisition can be performed in only one linear movement of the target.

3.3. Alignment of the CAD model with the acquired could of points (registration procedure)

To perform the alignment between the CAD model and the acquired cloud of points a procedure, based on Iterative Closest Points (*ICP*) optimization methods, has been developed and directly integrated in the laser scanner device. As a result of this procedure a roto-translation matrix is communicated directly to the robot controller.

The two sets of data input are:

- the 3D points of the last coupled with the gripping device in the CAD model $X_{pc\text{-}cad}$;
- the 3D points acquired by the *LSS* $X_{pc\text{-}laser}$

The goal of the alignment procedure, consists of identifying (registration process) the 3D rigid transformation (rotation $R_{pc\text{-}cad}$ and translation $T_{pc\text{-}cad}$) between the CAD nominal model and the 3D object reconstructed by the LSS (each point is expressed in the same Cartesian frame). Mathematically, the problem can be expressed as:

$$X_{pc-cad} = R_{pc-cad} \cdot X_{pc-laser} + T_{pc-cad} \qquad (11)$$

Iterative algorithms allow an easy and cost-efficient solution; target accuracy can be fixed by defining a user-selected tolerance threshold $\tau>0$ that identify the exit condition for the algorithm (iteration terminates when the mean-square error is below the threshold).

3.3.1. Registration algorithm

Despite the clouds of points are known in two different reference frames, the idea is to consider the two reference frames as if they were the same. Under this assumption the two clouds describes the same object in two different poses of a unique reference frame. Let us denote as:

- PS={psj} cloud of points acquired by the scanner, with j=1..N
- PC={pci} cloud of points extracted from the CAD model, with i=1..M

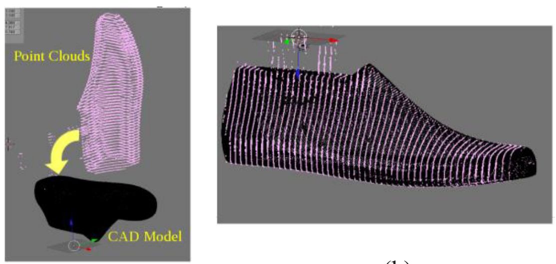
Where N and M are the number of points used for each clouds. They are obtained by sub-sampling the original clouds of points. Given each scanner-point ps_j, let denote as k^j_{min} the index of the cad-point that minimize the distance with respect to the *j*-th laser-point. Mathematically is expressed as:

$$k^j{}_{\min} \text{ such that } \left\| ps_j - pc_{k^j,\min} \right\| < \left\| ps_j - pc_i \right\|, \qquad (12)$$
$$k^j{}_{\min} \in 1...M \quad \text{and} \quad \forall i \in 1...M$$

Given the resulting set $\{k^j_{min}, j=1...N\}$, which is the correspondence of *PS* in *PC*, the least squares registration is computed by minimizing (as described above) the objective function:

$$\Sigma^2 = \sum \left\| pc_{k^j,\min} - \bar{R} \cdot ps_j - \bar{T} \right\|^2 \qquad (13)$$

The identification of the roto-traslation allows, as a consequence, the off-line modification of the robot tool path in order to compensate the coupling errors.



(a) (b)

Fig. 5. (a) points cloud before registration; (b) points cloud after registration

4. System Validation

4.1. Experiment description

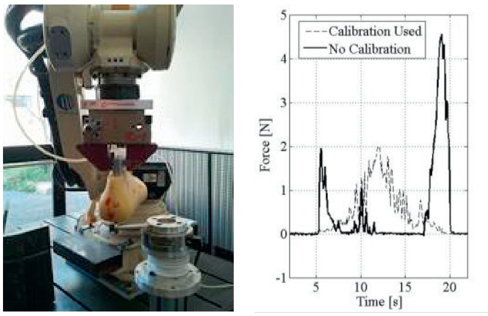
The experiment simulates the shoe-roughing application. The experiment consists of three different phases:

- An appropriate gripping device has been mounted on the last manually, such that errors in the device-alignment are introduced.
- A roughing trajectory is calculated by CAD/CAM and expressed in a frame centered nominally in the center of the gripping device.

- The shape of the last coupled with the gripping device is acquired by the LSS
- The compensation i.e. the 3D rigid roto-translation is calculated
- The robot is asked to bring the last in contact with a wheel simulating the roughing tool. The operation is performed twice with and without compensation; interaction forces between the last and the wheel are measured by means of a force sensor

Table 1. Experimental Set-up

	Data
Robot COMAU	NS16 (6dof, payload 16 kg)
Programming Language	PDL2
Force/torque sensor	ATI-DELTA6090, Analog Interface
Acq. Channel	Ethercat® modules, 1 kHz
Gripper	Shunk JGP160



(a) (b)

Fig. 6 (a) Setup with the robot, gripper, last and gripping device, force sensor and wheel connected to the force sensor; (b) measured forces at contact.

4.2. Experiment results

Fig.6 reports the experiment results. Without correction, the path followed by the robot is erroneous: zero-forces between time *11s* to *16s* means that contact is lost, while a high force peak of more than *4N* is achieved at time *18s*. Considering the repetition with the part program correction, the last is always in contact with the wheel. However, an increasing of the contact forces is still present when the robot moves towards the shoe tip. This is due to a valuable difference from the CAD model and the actual last.

Acknowledgements

This work is partially funded by ROBOFOOT project FP7-2010-NMP-ICT-FoF (260159), “Smart Robotics for high value added footwear industry”.

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