A Sensor Data Fusion-Based Locating Method for Reverse Engineering Scanning Systems

Andrea Rega
dept. of Industrial Engineering
dept. of Neuroscience, Reproductive and Odontostomatologic Sciences
University of Naples Federico II
Naples, Italy
andrea.rega@unina.it

Stanislao Patalano
dept. of Industrial Engineering
University of Naples Federico II
Naples, Italy
stanislao.patalano@unina.it

Ferdinando Vitolo
dept.of Industrial Engineering
University of Naples Federico II
Naples, Italy
ferdinando.vitolo@unina.it

Salvatore Gerbino
dept. of Engineering
University of Campania Luigi Vanvitelli
Aversa, Italy
salvatore.gerbino@unicampania.it

***Abstract*— The measurement of geometric deviations within large-size products is a challenging topic. One of the most applied technique compares the nominal product with the digitalization of real product obtained by a reverse engineering process. Digitalization of big geometric models is usually performed by means of multiple acquisitions from different scanning locations. Therefore, digitalization needs to correctly place the acquired point clouds in 3D digital environment. For this purpose, it is very important identifying the exact scanning location in order to correctly realign point clouds and generate an accurate 3D CAD model.**

The present paper faces the locating problem of a handling device for reverse engineering scanning systems. It proposes a locating method by using sensor data fusion based on Kalman filter, implemented in Matlab environment by using a low-cost equipment.

Keywords— Kalman filter, Position measurement, Product design, Prototypes, Reverse Engineering, Sensor data fusion.

I. Introduction

Reverse engineering (RE) of geometric models [1] has become increasingly relevant in many fields, such as, architectural [2], archaeology and cultural heritage [3], topographic [4], industrial [5], [6] food [7] and medicine [8] [9]. It aims to generate a digital mock-up (DMU) [10] of real products/components that could be used in a synergistic way with several designing methods [11]. RE is taking on a key role as inspection technique [12] supported by virtual reality (VR); in particular, DMU of real products is very useful for quality control, performance evaluation [13]-[16] and virtual maintenance applications [17], [18]. Besides, it improves the comparison between CAD model and real product allowing an automated and easier defect detection [19].

RE is based on the transfer of real surfaces to digital forms accomplished by scanning points of the 3D environment. There are several scanning devices with different operating characteristics in terms of accuracy and speed. The most used types are based on full-field (vision, laser, etc.) and point-by-point technology [20]-[22]. Although point-by-point systems are characterized by high accuracy, they are affected by slow acquisition process. Vice versa, full-field systems are characterized by high acquisition process allowing to quickly acquire large and complex geometries. On the contrary, they require multiple acquisitions from different locations, and then the realignment step of point clouds to control form error [23]. In such a case, the reference system of the device moves in relation to the global reference affecting the final CAD model accuracy [24].

The impact of the realigning process increases as much as the product size increases because it requires more acquisitions which are affected by more locating errors of the device reference system.

There exist three main point clouds realignment procedure based on: (i) common features among acquisitions, it needs object rich in features and requires post process actions by user; (ii) marker placed on the object, it needs to apply recognition elements on the object or in the surrounding space and it requires user actions as well; (iii) device reference system tracking, it enables the automatic point clouds realignment without user actions. It is very useful to acquire big size and featureless objects guaranteeing a high accuracy.

For example, in aerospace industry, airplane's wings are characterized by significant size, lack of different features and no interaction with surfaces is a mandatory constraint to assure during acquisitions. DMU of the inner fuselage can be useful for inspection application. Fuselage assumed as a tube, can be acquired, section by section, using a scanning system fixed on a handling device which moves along a collinear rail with the fuselage axis. The acquired section has to be placed in 3D digital environment according to the exact location of the device reference system, defined by the handling device movements.

The main challenge is to establish for each acquisition the exact location of the device reference system referred to the global one.

The present paper focuses on small size handling device to enable easier change of position and inner acquisition of objects. It faces the handling device locating problem by using a sensor data fusion (SDF) [25] based on Kalman filter [26][29]. The key idea is to develop a redundant measurement system to minimize the locating error of the handling device improving digital forms accuracy.

In the following, section 2 introduces the problem formulation and section 3 presents the locating method. Results are described and discussed in section 4. Finally, conclusions are given in section 5.

978-1-7281-0429-4/19/$31.00 ©2019 IEEE

II. PROBLEM FORMULATION

RE systems accomplish a form digitalization by means a scanning system (laser, photogrammetry and more). Scanning system feauters are usually used to classified a RE system. In our context, RE system is classified by means of two subsystems: scanning system and handling system which carries the scanning system. Handling system moves during acquisition and it is directly responsible of the realignment quality. In fact, scanning system refers the acquired points in its coordinate reference frame while the handling system defines the relative location referred to the global one.

Given an acquired point $\boldsymbol{P}$, its location can be referred to the scanning reference $\mathbf{O_1}$ by means of $\mathbf{p^1}$ vector. The location of the point $\boldsymbol{P}$ is referred to the global reference $\mathbf{O}_0$ by means of $\mathbf{p^0}$ vector. The scanning reference $\mathbf{O_1}$ is referred to the global reference $\mathbf{O}_0$ by means of $\mathbf{o_1^0}$ vector (Fig. 1).

If $\mathbf{R_1^0}$ is the rotation matrix of scanning reference referred to global reference, the position of point $\boldsymbol{P}$ referred to the global reference can be expressed as

$$p^0 = o_1^0 + R_1^0 p^1 \tag{1}$$

Considering movements in a Cartesian plane along y-axis direction, eq. (1) can be write as follow:

$$\begin{Bmatrix} p_{x_0}^0 \\ p_{y_0}^0 \\ p_{z_0}^0 \\ 1 \end{Bmatrix} = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & o_{y_0}^0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} q_{x_1}^1 \\ p_{y_1}^1 \\ p_{z_1}^1 \\ 1 \end{Bmatrix} \tag{2}$$

where the homogeneous transformation matrix (4x4) referrers the scanning reference $\mathbf{O_1}$ respect to the global reference $\mathbf{O}_0$.

The proposed method aims to exactly estimate $\boldsymbol{o_{y_0}^0}$ which correspond to the device's displacement along y-axis.

III. LOCATING METHOD

The proposed locating method is based on Kalman filter by fusing multiple and redundant measurements [24] in order to reduce the positioning error by a static correction of the location.

Fig.2 depicts the acquisition process. It is characterized by four steps: (S1) sub-tasks definition – it splits the main task by an evenly spaced movement steps according to the scanner operation parameters. The computed step movement is assumed as sub-task target; (S2) the actuator system turning on until the sub-task's target is reached; (S3) estimation of the current location by using sensor data fusion evaluating locating error; (S4) correction action to move on the target;

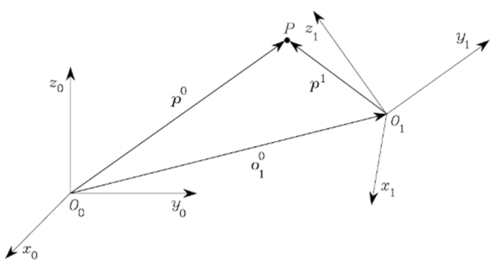

Fig. 1. Reference system.

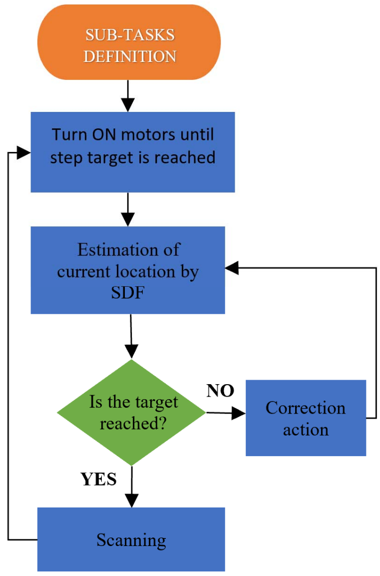

Fig. 2. Proposed acquisition process

The locating method concerns the step 3. It is mainly characterized by redundant sensors which measure the same quantity. Our method uses two signals generated by two sensors: (i) ultrasonic sensor; (ii) incremental rotary encoder. Due to different sensor accuracy, technology and position, sensors return different values. It firstly predicts location by means the odometry model and encoder's data, then it fuses ultrasonic's data.

A. Odometry Model

The RE system position is represented in the global reference $\mathbf{O}_0$ by its central point $\mathbf{O_1}$ with Cartesian coordinates $(x_{1,t}, y_{1,t})$ at time t. The local coordinates system $\mathbf{O_1}$ is fixed to the device.

Therefore, the device's location at step $t+1$ is described by the following odometrical model:

$$\begin{cases} x_{0,t+1} = x_{0,t} + \delta\rho_t \cdot \cos\theta_{0,t} \\ y_{0,t+1} = y_{0,t} + \delta\rho_t \cdot \sin\theta_{0,t} \\ \theta_{0,t+1} = \theta_{0,t} + \delta\theta_{0,t} \end{cases} \tag{3}$$

where $\delta\rho_{0,t}$ is the movement length and $\delta\theta_{0,t}$ the elementary rotation from state t to $t+1$. Assuming no wheel's slippage, then

$$\Delta\rho_{0,t} = \frac{\Delta U_{L_t} + \Delta U_{R_t}}{2}$$
$$\Delta\theta_{0,t} = \frac{\Delta U_{L_t} + \Delta U_{R_t}}{b} \tag{4}$$

ΔU_{L_t} and ΔU_{R_t} are calculated using the right and the left encoders, respectively.

Refer to (2) and assuming a Gaussian distribution of the measurement noise, odometry model can be written in the compact form:

$$\mathrm{O}_{1,t+1} = f(\mathrm{O}_{1,t}, \delta\rho_{0,t}) + n_{\rho,t} \tag{5}$$

where $O_1 = [0, y_{1,t}]$ and $n_{\rho,t}$ denotes the system noise which models the uncertainties of the odometry model.

B. Measurement model

Let d_r the measurement of the ultrasonic sensor which is the distance between the marker with known position $(x_{0,m}, y_{0,m})$ and the ultrasonic sensor central point. The measurement model is given by:

$$z_t = \begin{bmatrix} x_{0,m} - d\cos\theta_0 \\ y_{0,m} - d\sin\theta_0 \end{bmatrix} \tag{6}$$

where $d = d_r + L$ is the distance between marker position and the central point of $\mathbf{O_1}$ fixed to the RE system.

Equations (6) defines the measurement model which can be written in the compact form (including noise):

$$z_t = h(O_{1,t}) + v_t \tag{7}$$

where v_t is considered zero-mean white noise.

C. Pose estimation

At time t_i, the location measurement z_{1i} and $z_{2,i}$ are coming from encoder and ultrasonic sensor, respectively. The estimated location depends by previous estimation at time t_{i-1} and new measures which are affected by an uncertainty expressed as standard deviation σ_{z_1} and σ_{z_2}.

The predicted location $y(t_i)$ is expressed as follow:

$$y_0(t_i) = \hat{y}_0(t_{i-1}) + z_{1,i} \tag{8}$$
$$\sigma^2_{y_0}(t_i) = \sigma^2_{\hat{y}_0}(t_{i-1}) + \sigma^2_{z_1}$$

In the updating stage the ultrasonic sensor carries out the measure and therefore the estimated location $\hat{y}(t_i)$ is expressed as follow:

$$\hat{y}_0(t_i) = y(t_i) + K(t_i)[z_{2,i} - y(t_i)] \tag{9}$$

with:

$$K(t_i) = \frac{\sigma^2_{y_0}(t_i)}{\sigma^2_{y_0}(t_i) + \sigma^2_{z_2}};$$
$$\sigma^2_{\hat{y}_0}(t_i) = \sigma^2_{\hat{y}_0}(t_{i-1}) + \sigma^2_{z_1}. \tag{10}$$

$K(t_i)$ is the Kalman Gain.

In RE context, the Kalman filter improves the alignment of point clouds by minimizing the mean square error of the estimated locations

IV. Results

The proposed method has been implemented by hardware-in-the-loop tests by using Arduino Uno rev3 programmed in Matlab/Simulink environment. Sensors were simulating by random signals with Gaussian distribution and zero mean.

We have set forward step of 100 mm and simulation ending condition on 1000 mm.

Table I shows the mean of the generating value for 20 iterations. Comparing errors diagram is depicted in Fig. 3. Dot line (green-square) represents the errors of the ultrasonic sensor; dashed line (red) represents the errors of the encoders, computed as difference between target value and average of the encoder's signal; solid line (blue-triangle) represents the estimated errors by using Kalman filter.

Kalman filter estimation is very close to the target with an average error lower than the two simulated sensors. Therefore, estimated location is more accurate than sensor measurements.

V. Conclusions

The present paper proposes a method to correctly locate a device for reverse engineering systems. It aims at improving accuracy of point cloud realignment and it is based on fusion of redundant sensors by using Kalman filter.

We have carried out hardware-in-the-loop tests by using Arduino Uno rev3 programmed in Matlab/Simulink environment. Tests was simulated up to a meter distance. Results show that the Kalman accuracy is better than the simulated sensors.

Therefore, considering use of low-cost hardware, the device behavior is encouraging and is open to future improvements.

Next step is the development of a handling device prototype with hardware sensors. Subsequently, we will develop a handling device integrated with the Reverse Engineering system; at the same time, more performing sensors and microcontrollers will be used to give better results in terms of reliability and accuracy.

TABLE I. Simulated Data

Step	Encoders	Ultrasonic sensor	Kalman filter	Target
1	100,024	100,105	100,085	100,000
2	199,985	200,042	200,031	200,000
3	299,874	300,112	300,065	300,000
4	399,880	400,031	400,002	400,000
5	499,884	500,078	500,040	500,000
6	599,982	600,074	600,056	600,000
7	700,009	700,104	700,085	700,000
8	800,023	800,045	800,040	800,000
9	900,112	899,798	899,859	900,000
10	999,735	999,967	999,967	1000,000

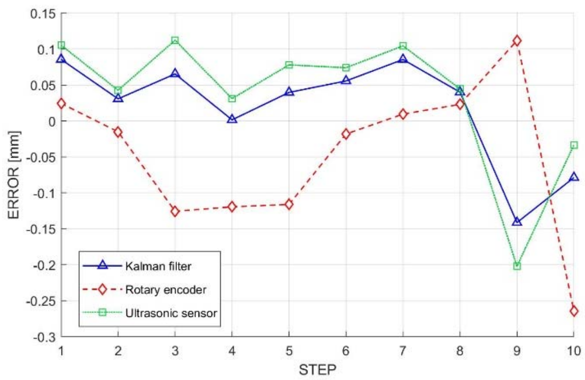

Fig. 3. Comparison between the errors of the generating signals (rotary and ultrasonic sensor) and the estimated position (Kalman)

Acknowledgment

The present work was developed with the economic support of MIUR (Italian Ministry of University and Research) performing the activities of the project ARS01_00861 "Integrated collaborative systems for smart factory - ICOSAF".

References

[1] Z. Geng, B. Bidanda, "Review of reverse engineering systems–current state of the art," Virtual and Physical Prototyping, vol. 12, no. 2, pp. 161-172, Mar. 2017.

[2] L. De Luca, P. Véron, M. Florenzano, "Reverse engineering of architectural buildings based on a hybrid modeling approach," Computers & Graphics, vol. 30, no. 2, pp. 160-176, Apr. 2006.

[3] V. Barrile, G. Bilotta, D. Lamari, "3D models of cultural heritage," International Journal of Mathematical Models and Methods in Applied Sciences, vol. 11, pp. 1-8, 2017.

[4] M.R. James, S. Robson, "Straightforward reconstruction of 3D surfaces and topography with a camera: Accuracy and geoscience application," Journal of Geophysical Research: Earth Surface, vol. 117, F03017, Aug. 2012.

[5] Z. M. Bi, L. Wang, "Advances in 3D data acquisition and processing for industrial applications," Robotics and Computer-Integrated Manufacturing, vol. 26, no. 5, pp. 403-413, Oct. 2010.

[6] Franciosa, P., Gerbino, S., Lanzotti, A., Silvestri, L. Improving comfort of shoe sole through experiments based on CAD-FEM modeling. Medical Engineering and Physics, 35 (1), pp. 36-46, 2013.

[7] J. A. García-Esteban, B. Curto, V. Moreno, I. González-Martín, I. Revilla, I., A. Vivar-Quintana, "A digitalization strategy for quality control in food industry based on Artificial Intelligence techniques," in IEEE 16th INDIN, Porto, Portugal, 2018, pp. 221-226.

[8] M. Martorelli, P. Ausiello, R. Morrone, "A new method to assess the accuracy of a Cone Beam Computed Tomography scanner by using a non-contact reverse engineering technique," Journal of Dentistry, vol. 42, no. 4, pp. 460-465, 2014.

[9] M. A. Ares, S. Royo, J. Vidal, L, Campderros, D. Panyella, F. Peréz, S. Vera, M. A. Gonzalez Ballester, "3D scanning system for in-vivo imaging of human body," Fringe 2013 - 7th International Workshop on Advanced Optical Imaging and Metrology, Nurtingen, Germany, 2014, pp. 899-902.

[10] G. Döllner, P. Kellner, O. Tegel, "Digital mock-up and rapid prototyping in automotive product development," Journal of Integrated Design and Process Science, vol. 4, no. 1, pp. 55-66, 2000.

[11] S. Patalano, F. Vitolo, A. Lanzotti, "Automotive power window system design: Object-oriented modelling and design of experiments integration within a digital pattern approach" Mechanics and Industry, vol. 17, no. 5, n.505, 2016.

[12] S. Gerbino, D. M. Del Giudice, G. Staiano, A. Lanzotti, M. Martorelli, "On the influence of scanning factors on the laser scanner-based 3D inspection process," International Journal of Advanced Manufacturing Technology, Vol. 84, no. 9-12, pp. 1787-1799, Jun. 2016, DOI: https://doi.org/10.1007/s00170-015-7830-7

[13] A. Lanzotti, F. Renno, M. Russo, R. Russo, M. Terzo, "Virtual Prototyping of an Automotive Magnetorheological Semi-Active Differential by means of the Reverse Engineering Techniques," Engineering Letters, vol. 23, no. 3, pp 115-124, 2015.

[14] A. Lanzotti, F. Carbone, G. Di Gironimo, S. Papa, F. Renno, A. Tarallo, R. D'Angelo "On the usability of augmented reality devices for interactive risk assessment". International journal of safety and security engineering, vol. 8, n.1, pp. 132-138, 2018.

[15] C. Labate, G. Di Gironimo F. Renno, "Plasma facing components: a conceptual design strategy for the first wall in FAST tokamak". Nuclear Fusion, vol. 55, n. 11, 113013, 2015.

[16] A. Lanzotti, F. Carbone, S. Grazioso, F. Renno, M. Staiano, "A new interactive design approach for concept selection based on expert opinion". International Journal on Interactive Design and Manufacturing vol 12, n. 4, pp. 1189-1199, 2018.

[17] A. Tarallo, R. Mozzillo, G. Di Gironimo, A. Aiello, M. Utili, I. Ricapito, "Preliminary piping layout and integration of European test blanket modules subsystems in ITER CVCS area," Fusion Engineering and Design, vol. 93, pp. 24-29, Apr. 2015.

[18] E. Martelli, A. Del Nevo, P. Arena, G. Bongiovì, G. Caruso, P. A. Di Maio, M. Eboli, G. Mariano, R. Marinari, F. Moro, R. Mozzillo, F. Giannetti, G. Di Gironimo, A. Tarallo, A. Tassone, S. Villari, "Advancements in DEMO WCLL breeding blanket design and integration," International Journal of Energy Research, vol. 42, p. 27-52, DOI: 10.1002/er.3750, 2018.

[19] P. Franciosa, A. Palit, F. Vitolo, D. Ceglarek, "Rapid Response Diagnosis of Multi-stage Assembly Process with Compliant non-ideal Parts using Self-evolving Measurement System", Procidia CIRP, vol. 60, pp. 38-43, 2017.

[20] S. Son, H. Park, K. H. Lee, "Automated laser scanning system for reverse engineering and inspection," International Journal of Machine Tools and Manufacture, vol. 42, no. 8, pp. 889-897, Jun. 2012.

[21] E. Trakić, B. Šarić, A. Osmanović, S. Lovrić, "Integration mechatric components of laser triagulation for 3D digitalization of the object," International Journal of Mechanical and Mechanics Engineering, vol. 11, no. 2, pp. 1-6, Apr. 2011.

[22] X. Zexiao, W. Jianguo, Z. Qiumei, "Complete 3D measurement in reverse engineering using a multi-probe system," International Journal of Machine Tools and Manufacture, vol. 45, no. 12-13, pp. 1474-1486, Oct. 2005.

[23] F.Vitolo, M. Martorelli, S. Gerbino, S. Patalano, A. Lanzotti, "Controlling form errors in 3D printed models associated to size and position on the working plane," International Journal of Interact Design and Manufacturing, vol. 12, no. 3, pp. 969-977, August 2018.

[24] G. Guidi, J. A. Beraldin, S. Cio, C. Atzeni, "Fusion of Range Camera and Photogrammetry: A Systematic Procedure for Improving 3-D Models Metric Accuracy," IEEE Transactions on Systems Man and Cybernetics Part B (Cybernetics), Vol. 33, no. 4, pp. 667-676, Aug. 2003.

[25] A. Weckenmann, X. Jiang, K. D. Sommer, U. Neuschaefer-Rube, J. Seewig, L. Shaw, T. Estler, "Multisensor data fusion in dimensional metrology," CIRP Annals, vol. 58, no. 2, pp. 701-721, 2009.

[26] R. E. Kalman, "A new approach to linear filterng and prediction problems," Transaction of the ASME-Journal of Basic Engineering, pp.35-45, March 1960.

[27] C. K. Chui, G. Chen, Kalman filtering. Springer International Publishing.

[28] C. Hu, W. Chen, Y. Chen and D. Liu, "Adaptive Kalman Filtering for vehicle navigation," Journal of Global Positioning Systems, vol. 2, no.1, pp. 42-47, 2003.

[29] J.Z. Sasiadek, P. Hartana, "Sensor data fusion using Kalman Filter," Proceedings of the Third International Conference on Information Fusion, vol. 2, no.5, pp. 19-25, 2000.