Optics and Lasers in Engineering 88 (2017) 82–90

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

High-accuracy and real-time 3D positioning, tracking system for medical imaging applications based on 3D digital image correlation

Yuan Xue [a], Teng Cheng [a], Xiaohai Xu [a], Zeren Gao [a], Qianqian Li [b], Xiaojing Liu [b], Xing Wang [c], Rui Song [c], Xiangyang Ju [d], Qingchuan Zhang [a,*]

[a] University of Science and Technology of China, CAS Key Laboratory of Mechanical Behavior and Design of Materials, Department of Modern Mechanics, Hefei, 230027 China
[b] Peking University School and Hospital of Stomatology, Department of Oral and Maxillofacial Surgery, Beijing, 100081 China
[c] Shandong University, School of Control Science and Engineering, Jinan, 250061 China
[d] Medical Devices Unit, DCPB, NHS Greater Glasgow and Clyde, Glasgow, UK

ARTICLE INFO

Article history:
Received 23 March 2016
Received in revised form
20 May 2016
Accepted 11 July 2016

Keywords:
3D digital image correlation (3D–DIC)
Real-time tracking
Medical imaging

ABSTRACT

This paper presents a system for positioning markers and tracking the pose of a rigid object with 6 degrees of freedom in real-time using 3D digital image correlation, with two examples for medical imaging applications. Traditional DIC method was improved to meet the requirements of the real-time by simplifying the computations of integral pixel search. Experiments were carried out and the results indicated that the new method improved the computational efficiency by about 4–10 times in comparison with the traditional DIC method. The system was aimed for orthognathic surgery navigation in order to track the maxilla segment after LeFort I osteotomy. Experiments showed noise for the static point was at the level of 10^{-3} mm and the measurement accuracy was 0.009 mm. The system was demonstrated on skin surface shape evaluation of a hand for finger stretching exercises, which indicated a great potential on tracking muscle and skin movements.

1. Introduction

3D Digital image correlation (3D–DIC, also called stereo DIC) is a non-interferometric and non-contacting optical metrology for full-field shape and deformation measurements. Originated in the 1980s [1–3], after the development of more than 30 years, it has been widely used in experimental mechanics and other scientific fields [4–11], which also gives inspirations in medical imaging applications. There have been reports of medical related applications and experiments based on 3D–DIC. For example, Sztefek et al. used 3D–DIC to measure the bone surface strains of the mouse tibia [12]. Shao et al. used 3D–DIC to record tiny fluctuation caused by pulses on the wrist skin [13]. Hokka et al. used the 3D–DIC technique on analyzing of the myocardial movement during a cardiopulmonary bypass surgery [14]. Most reports usually focused on the post-processing of the images of a continuous surface, while real-time 3D positioning and tracking were not considered. In fact, the real-time 3D positioning and pose tracking are essential in surgical navigation and the observation of the muscle and skin movement. This paper presents a system for positioning markers and tracking the pose of a rigid object in real time. In a matching process between reference image and deformed image, integral pixel search and sub-pixel iterations are the main steps in DIC method. In the last decade, a lot of research have been carried out in order to enhance the computational efficiency of the DIC [15,16]. Most of the research usually focus on the post-processing process for a continuous surface reconstruction and the improvements of sub-pixel iterations. The computational efficiency of integral pixel search without optimization was still time-consuming and was too slow to meet the real-time requirements.

In the paper, a real-time system for markers positioning and pose tracking was proposed and tested. The computational efficiency was improved by simplifying the computation of integral pixel search of DIC. Equidistant search was set properly instead of global search according to the radius of convergence of sub-pixel iteration. Parallel computing was applied to integral pixel search to further improve the search efficiency. Practical implements proved that the method was simplified and efficient.

Achieved real-time tracking, a navigation system for tracking maxilla after LeFort I osteotomy [17] was established initially. Compared to infrared optical tracking, which was the main method in the current surgical navigation, 3D–DIC can achieve high precision and non-expensive 3D positioning and tracking with small markers. During the navigation, the segment of the

* Corresponding author.
E-mail address: zhangqc@ustc.edu.cn (Q. Zhang).

http://dx.doi.org/10.1016/j.optlaseng.2016.07.002
0143-8166/

maxilla was tracked with 6 degrees of freedom.

At last, a demonstration of real-time tracking of ink markers and post-processed surface reconstruction of a hand in a time series for finger stretching exercises was presented to show the potential in observing muscle and skin movements.

Section 2 will briefly introduce the DIC algorithm integrated in the system, which is the foundation of the new work. Section 3 will present the optimization of the coarse search process to meet the real-time requirements. Section 4 will illustrate two examples on medical imaging applications realizing markers positioning and pose tracking for rigid body.

2. System integration and process of 3D–DIC

In the DIC method, point of interest (POI) and its neighborhoods are used for image matching (subset matching). In order to perform image matching accurately, a subset must have enough, distinct, isotropic texture. Based on the requirements above, speckle, as a kind of random texture, is the best choice. Fig. 1 shows the speckle generated by computer or sprayed by paint. During the matching process, correlation function is used to evaluate the similarity between the reference subset and the target subset. In this system, Zero-mean Normalized Sum of Squared Difference (ZNSSD) is used as the correlation function.

Current process of 3D–DIC is usually divided into two steps: integral pixel search and sub-pixel iteration. Integral pixel search is a coarse search. As shown in Fig. 2(a), POI P(x, y), subset and search area are set on the reference image. After the object moves or deforms, deformed image is acquired. In the Fig. 2(b), the center of the search area is POI in the previous image. Target subsets is set whose center is all the integral pixel position in the search area. The most relevant target subset is chosen according to correlation coefficients between target subsets and reference image. The center of the target subset is the result of the Integral pixel search. This method of coarse search is the traditional integral pixel search in DIC.

The coarse search can only reach integral pixel accuracy. For higher accuracy, sub-pixel iteration is introduced. In the process of integral pixel search, the correlation function is limited to the square subset, but in actual process, a square reference subset is usually deformed to a quadrangle. Shape function used in sub-pixel iteration is to describe the deformation. Linear shape function can describe the translation, rotation, and uniform shear and stretching deformation, which is enough for most situations [18]. In this work, L–M (Levenberg–Marquardt) iteration method was used. As shown in Fig. 2(c) and (d), the result of the integral pixel search was the initial value of the iteration. If the iteration converges, the final result was considered as a successful match.

In the system as shown in Fig. 3, the first image of the left camera is set as reference image and other images were all deformed images. This strategy is chose because of faster computational efficiency, compared to other strategies [15,19]. During the calculation, the search area was updated. At last, according to the calibration, the 3D coordinates were obtained.

The system also integrates synchronous image capture, camera calibration and 3D reconstruction for convenient use. New improvements of the system for medical real-time requirements is in chapter 3. And partial results are carried out by the commercial version software PMLAB (PMLAB DIC-3D; Nanjing PMLAB Sensor Tech Co., Ltd., Nanjing, China).

3. Improvements for real-time requirements

In the usual DIC calculation for a continuous surface, the integral pixel search only need to perform once by using a seed point to expand [20]. But for tracking discontinuous markers, each marker in each stage need to perform the integral pixel search. In our statistics, the traditional integral pixel search takes up more than 95% of the total computing time in the matching process. To improve the efficiency in coarse search, some searching strategies and algorithm has been proposed. For example, Zhang et al. developed a coarse–fine search using affine transform [21] and Huang et al. invented a new recursive algorithm based on Fast Normalized Cross Correlation [22,23]. But these methods above are not suitable for discontinuous markers or parallel computation. In recent years, most of the research on real-time 3D–DIC focus on the sub-pixel iteration, which is used for a continuous surface. The efficiency of integral pixel search is still too slow to meet the real-time requirements. To our knowledge, previous reports on real-time tracking based on DIC is within several pixels (Refs. [13,24]), because of limitation of convergence radius in sub-pixel iteration.

In the paper, a new method for integral pixel search was proposed. As shown in Fig. 4(a), the traditional integral pixel search searches the target subsets in order. Compared to traditional method, Fig. 4(b) shows search interval was set to simplify the computations and parallel program was designed for each target subset. So the coarse search did not need calculate all the target subsets in search area. The proper value of interval was relevant to the radius of convergence in sub-pixel iteration. If the interval was bigger than the radius of convergence, a wrong match may be obtained, because the initial value for iteration was too far to converge to the real position. It was found that not only the iteration algorithm had an impact on the radius of convergence, but also the pattern of speckle played an important role.

3 kinds of speckle were choose to test the convergence radius. An Image including these speckle patterns was acquired and selections is displayed in the same 29*29 pixel size as shown in

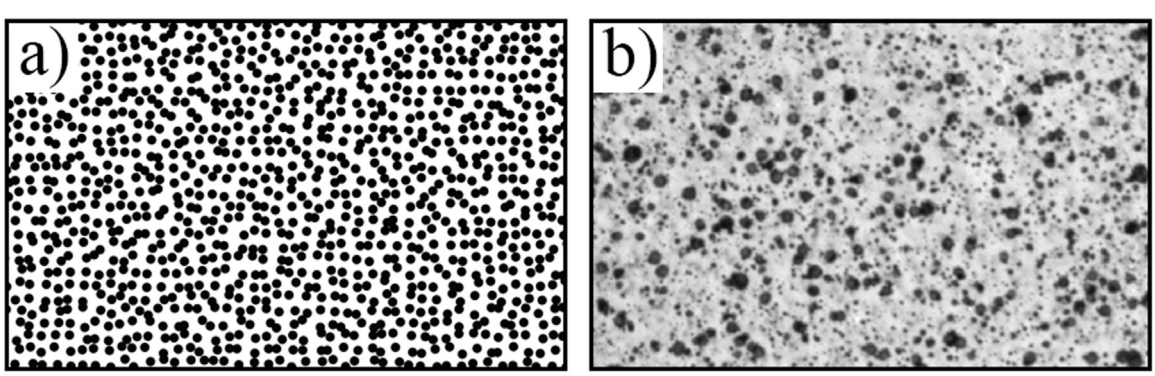

Fig. 1. (a) Is the speckle generated by computer, and (b) is the speckle sprayed by paint.