A ROBUST, ACCURATE AND LOW COST C-ARM BASE-TRACKING SYSTEM

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INTRODUCTION

Different factors must be addressed to allow C-arms to provide quantitative (positional) information; the most important of these is to track the pose (position and orientation) of the device itself. The X-ray images provided by the C-arm can be used for image-based procedures, such as image-based navigation, panoramic X-ray generation, X-ray mosaics and X-ray image processing, if and only if the pose of the source-detector set (corresponding to the time of exposure) is accurately known. This illustrates the necessity of an accurate tracking system that can provide the real-time pose of the device for each X-ray shot.

Although different off-line C-arm joint-tracking systems have been reported in the literature (Amiri 2011; Amiri 2013; Reaungamornrat 2012; Grzeda 2011), optical-based systems are costly and require a large field of view if the C-arm is moved in and out of the surgical field, whereas non-optical (e.g. accelerometer-based) systems to date have all required a fixed (stationary) C-arm base, to our knowledge.

Since there are cases where images need to be acquired over a longer distance, as in panoramic registration of the images (Amiri 2013), or over a larger working volume, our goal was to design a low-cost base-tracking system capable of reporting the real-time two-dimensional (2D) position and orientation of the C-arm base. These data can be integrated with any joint tracking system to recover the full six degree-of-freedom (DOF) pose of the device for any X-ray of interest. This has two purposes: 1) to report the current base pose, and 2) to return to a defined position. These can be valuable with or without C-arm joint tracking, wherever precise and repeatable positioning of the base is desired. The base-tracking system can also benefit optical joint-tracking systems by limiting the required field of view to the operating field, tracking the base as it is moved in and out of the field of view.

The desired system must be accurate, robust, retrofittable, inexpensive and as dimensionally small as possible. Based on observations at surgeries attended, moving the C-arm in and out of the surgical field requires approximately 3 to 4 m of total travel. For this distance, accuracy better than 3% of the total absolute cumulative distance changes would be needed to return the base to within 10 cm of the original location (half the size of imaging plane to ensure that the desired object appears in the acquired fluoroscopic imagery after moving the C-arm back to the surgical area). Acceptable orientation accuracy was defined as better than 3°[1] of the total cumulative orientation changes. Given the constraints of the operating room, the C-arm would rarely be rotated more than 30°, resulting in a total excursion of 60°. Under these circumstances, an orientation accuracy within 5% would be sufficient. The purpose of the present study was to develop and test the proposed system.

MATERIALS AND METHODS

Amongst all available dead-reckoning systems (e.g. encoder-based systems, optical flow sensors), *visual odometry* (VO) appears to satisfy the expectations of the specific application of this research to the greatest extent. An application-specific monocular visual odometry

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[1] $\arctan\left(\frac{5}{150}\right)$; base-centre to image-centre: 1.5 m plus a desire to make no more than 5 mm translational error.

system is proposed in this research. The proposed structure of the C-arm-specific visual odometry system consists of a downward-looking consumer-grade camera, rigidly attached to the base platform of the device, and a processing (software) module that is capable of estimating the 2D real-time movement of the camera-carrying platform (C-arm base). Acquired frames are first undistorted to correct for the possible effect of lens aberration, based on data achieved from a previously established calibration process (Esfandiari 2014). A well-known optical flow algorithm (Lucas 1981) is then utilized to extract the corresponding features within the consecutive frames. The proposed sensory configuration assumes that the pixel array plane is perfectly parallel to the operating room floor, however, in order to correct for deviations from perfect perpendicularity of the camera's imaging plane to the underlying floor normal, a perspective rectification process is designed. In this stage, the acquired frames are analytically rectified as if the camera is kept parallel to the floor. The undistorted and rectified coordinates of the corresponding features (extracted based on the optical flow estimation) are then utilized to feed the odometry estimation system. The cumulative dead-reckoning estimation of the moving base is extracted based on frame-to-frame homography estimation and decomposition. Online positional and orientation parameters are then reported. The overall workflow of the proposed method is illustrated in Fig. 1.

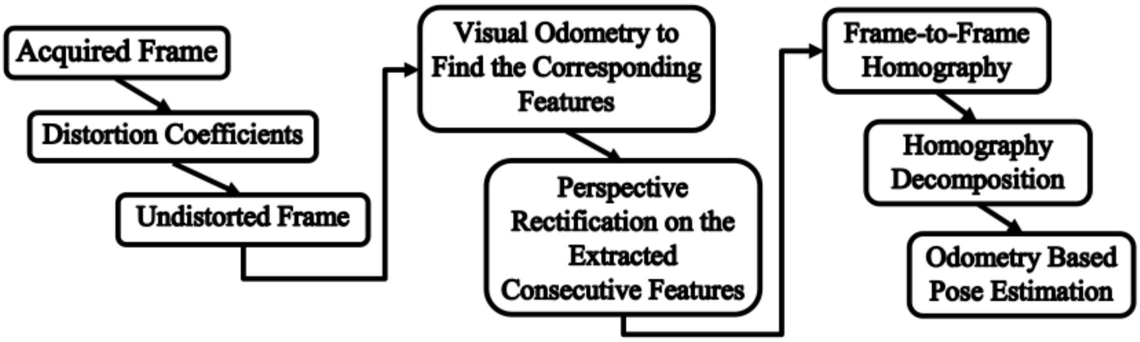

Figure 1: Schematic workflow of the base-tracking system.

Any dead-reckoning system can be exposed to different error sources due to the open-loop concept of the odometry. This is a serious concern for long-range movements in which the individual errors of each epoch can easily get accumulated and cause the tracking outcomes to deviate from the real trajectory of the moving platform ("relative tracking"). In this study we have introduced a loop closure procedure ("absolute tracking") that can solve for the accumulated odometry errors after observing a physical ground pattern (attached to the surgical room floor in one or more locations) to bring back the tracking results to the desired location or trajectory.

A GigE vision[2] grayscale camera was exploited in this study (BFLY-PGE-09S2M-CS, Point Grey Research Inc., Vancouver, Canada). A custom-made experimental setup was used to replicate the actual changes in translation and orientation of a C-arm base (Fig. 2). Performance of the proposed visual odometry system was tested under various situations including different: camera heights, movement ranges, movement velocities and floor textures. Repeatability was analysed by recovering the measured odometry results for the setup base line and for the camera height of approximately 70 cm. The feasibility of the proposed tracking system was also investigated on real or floor textures.

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[2] Global camera interface standard developed using the Gigabit Ethernet communication protocol

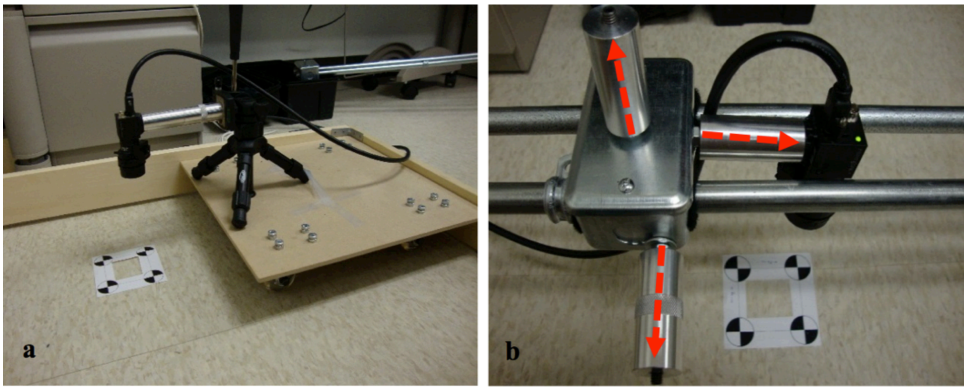

Figure 2a: Rotating platform with a right-angled reference; b: Sliding platform with three camera-mountable shafts shown with red arrows.

RESULTS

Positional accuracy of better than 2% of the total traveled distance for most of the cases and 4% for all the cases studied (Fig. 3) and angular accuracy of better than 2% of absolute cumulative changes in orientation (Fig. 4) was achieved with this method. Repeatability results were 4.5 mm (SD, 3.1 mm) from the ground truth. System accuracy in all of the investigated floor textures (parquet, office floor, carpet and tile) was better than 2% of the traveled distance (Table 1). The number of trackable features ranged from 479 to 1000 for the real operating room floors. Increasing the velocity of platform movement caused degradation in accuracy of the odometry results. The performance of the translational loop closure was better than 1 mm over 3 cm (0.33%).

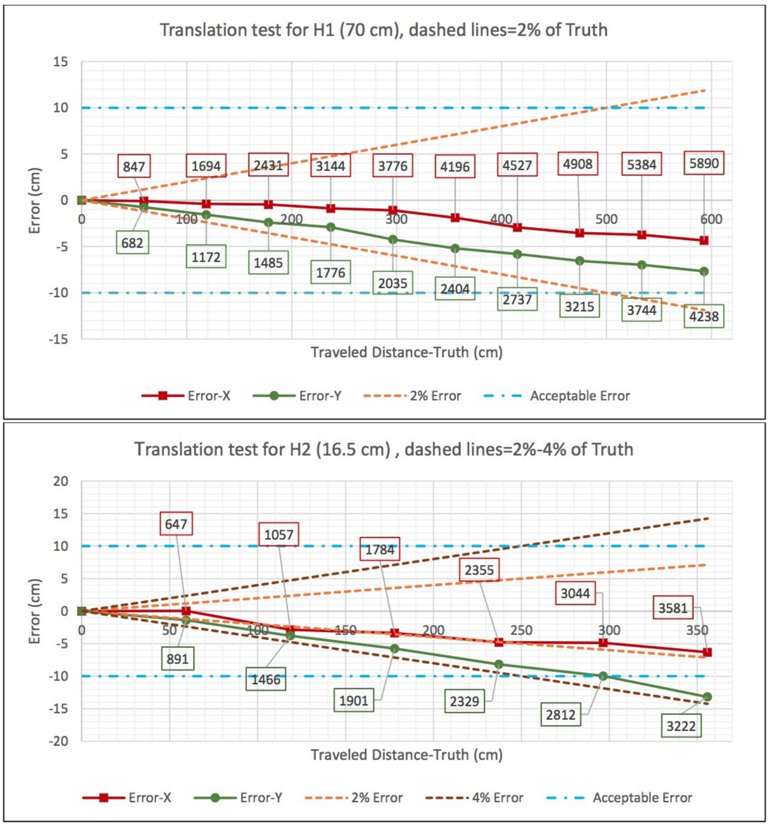

Figure 3: Errors for ~6 m translation tests for H1=70 cm and H2=16.5 cm. Dashed lines=2% and 4% of truth; numbers in the boxes: Frame#; Red: movement conducted along the X-axis of the image; Green: movement conducted along the Y-axis of the image.

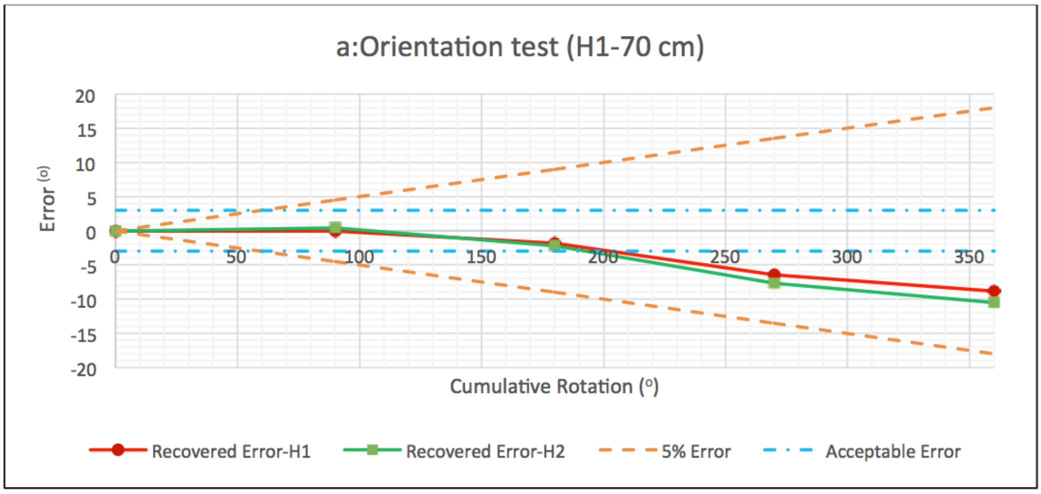

Figure 4: Accuracy of orientation recovery.

Table 1: Tracking results for different floor textures.

Floor Texture		Tile	Carpet	Mosaic	Parquet
Translational Error*	H1**=70 cm	0.4%	0.8%	0.4%	0.4%
	H2=16.5 cm	1%	0.4%	2%	0.8%

(*) Percent of the total (~2.5 m) traveled distance.
(**) Camera height from the floor.

DISCUSSION

This study presented an algorithm and experimental testing results of a C-arm base-tracking system. The method offers a robust, accurate, retrofittable and inexpensive C-arm base-tracking solution that can be added to any C-arm (together with an interface). The only employed sensory unit in this system is a consumer-grade monocular camera, which makes the setup capable of being integrated with existing devices. The performance of this system was examined under different situations to evaluate the final tracking results for actual manipulation. As shown by the experimental results, one can expect the system to provide final translational and rotational accuracies of less than 2% (with respect to the total travelled distance and rotation) in most of the cases studied, and substantially less if loop closure is used.

The experimental analysis revealed that the higher the distance of the camera to the underlying floor, the better the accuracies of the system. This is due to the fact that, as the camera increases its distance from the underlying floor, its field of view will increase resulting in observing more trackable features and consequently higher redundancy in estimation. As the camera increases its distance from the floor, the observation scale decreases, resulting in less sensitivity of the recovered pose to the odometry errors. However even for the camera distance of 16.5 cm the system performed with external precision of better than 2% for most of the cases and less than 4% for all the cases (almost 4% for H2 and for displacement along the y axis). The movement velocity was shown to have a direct impact on the tracking errors, meaning that the correctness of the recovered platform pose was higher for lower movement velocities. This is due to the significant motion blur appearing in the acquired frames at higher speeds. Therefore, higher temporal resolutions (frame rates) are highly recommended for future implementations. Thanks to the robustness of the KLT optical-flow estimator after tuning the parameters of the feature extractor, this method reached the acceptable ranges of accuracy for different floor textures. It can be claimed, based on presented experiments in which considerable texture was found on real operating room floors, that this system is capable of providing robust base-tracking results in real clinical applications.

A 10 cm error range over 6 m displacement conducted in 150 s was defined as the performance norm to be compared with existing systems. Comparing the accuracy of the proposed method with the current VO systems found in the literature (19.6 cm error over 6 m of displacement (Campbell 2005); 76.5 cm error over 150 s of movement (Forster 2014) and maximum error range of ~6% (Silva 2012)) and considering the application-specific criteria (that limits the performance of a forward-looking camera) this method is capable of providing either more accurate or more appropriate solutions for the C-arm base tracking.

According to acceptable accuracies above and based on the results reported in this study, the relative odometry results can be utilized to satisfy the expected accuracies when the total movement of the device is less than 3 m. This is enough for most of the clinical cases; however, for longer movements, the presented loop closure procedure is recommended by incorporating ground-truth landmarks on the surgical floor.

The system currently operates in stop-and-go off-line mode due to limitations in the camera communication software development kit; development of an online version is scheduled for future phases of the research. Parallel processing methods will be of interest in future implementations of the software to allow for real-time processing. Another main limitation for the proposed method is the non-intelligent trackable-feature selection across the acquired frames. This can be developed and replaced with selective approaches to guarantee the diverse presence of features all over the successive images.

High localization accuracy of this method can be of interest for any application in which real-time location of a moving platform is needed. This method satisfies the required clinical base-tracking accuracies as long as either (a) the excursion distance is kept within 3 m, and a reasonably slow velocity is used, or (b) loop closure (absolute tracking) is used to reset the location once the reference is within view. This system is expected to be integrated with the TC-arm system (Amiri 2013) and other C-arm technologies in the near future to deliver a full degree-of-freedom C-arm tracking system and quantitative analysis capability to improve the surgical outcome.

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