EXPERIMENTAL SETUP FOR EVALUATING THE ACCURACY OF MARKERLESS HUMAN MOTION ESTIMATION TECHNIQUES

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1. INTRODUCTION

Human Movement Analysis is generally performed through the exploitation of stereophotogrammetric systems that rely on the use of markers [3]. With these systems, it is possible to reconstruct the trajectories of reflecting objects allocated on specific points of the human body and it is possible to reconstruct limb kinematics through the calibration parameters. In order to reduce measuring errors and artefacts dedicated algorithms are used.

The performance of these systems are evaluated through the accuracy of kinematics estimation, using a range of tests of “spot-checks” developed to this purpose. There are two kinds of tests: static and dynamic ones. The first tests are based on the estimation of distances between markers, whose mutual distance is known. The second ones are based on the reconstruction of known trajectories (i.e. rotating disk test, gravity test etc.[7]).

An example of static spots-check is the “Movement Analysis Laboratory” test (MAL test [5]): a stiff bar, that presents an extremity laid on a point of the fixed reference system, is used. Two markers are placed on the bar in two different points. The accuracy is evaluated by estimating the coordinates of the extremity as the intersection of the straight line detected by the markers in different positions.

An example of dynamic spots-check is the “gravity test”: a rigid pendulum, that presents two markers placed on the extremities, is let be swinging. The accuracy is evaluated comparing the trajectory of the swinging extremity, estimated with the use of markers, with the real one.

Marker based systems show relatively high costs while the procedure is generally time consuming and uncomfortable for the patients. In some applications, the use of these specialized systems can be replaced by the utilization of video capture systems that do not necessarily rely on marker application, together with specific image processing techniques for detection and tracking of relevant body points.

As it has been done with stereophotogrammetric systems, it is also necessary to define some protocols useful to evaluate the accuracy of markerless systems in the estimation of kinematic parameters. This is possible by using the same rationale of previous “spot-checks” tests concerning stereophotogrammetry, but it is necessary to evaluate specific problems connected with markerless systems and to define an adequate experimental setup.

In order to manage this problem, a protocol has been defined and developed considering three significant phases:

1) Establishing kinematic features of a mobile reference system through a direct measure in order to have a valid term of comparison.
2) Estimating kinematic features of the mobile reference system through image processing techniques, using dedicated algorithms.
3) Comparing kinematic features through statistical analysis choosing appropriate evaluation parameters.

This work aims at defining a valid experimental setup to evaluate the accuracy of two markerless techniques when used to estimate motion from videos: a Block Matching Algorithm and a Transformed Domain approach.

2. MATERIALS AND METHODS

In order to evaluate kinematic quantities, an instrument that reproduces scaled version of human-like simple movement has been realized. This instrument is composed by a turning circular plane because human limb movements show a prevailing rotating component.

A rotating disk is used to test the potentiality of the technique to track point trajectories both at high and low rotation frequencies. The analysis of videos recorded during disk rotation has allowed to quantify the accuracy of a 2D motion-estimation technique. A 30 cm diameter aluminium plate has been connected to an electric AC induction motor with a transmission strap so that it could rotate around a vertical axis. The transmission ratio (1:33) between motor and plate produces angular velocities in the range 10÷45 rpm, by changing the input voltage. In order to estimate the movement, a scaled 1:6 human dummy has been fixed on the plate. A polar coordinates reference system has been considered in order to evaluate the relative position of relevant body points of the dummy. Some markers have been placed on these points in order to compare the motion estimation accuracy with or without them. The reference
velocity has been measured by a light emitter-detector device, thus allowing to determine the dummy nominal kinematics. The experimental setup is equipped with a digital commercial camera which acquires videos, at 30 frames/s with a resolution of 640x480 pixels. Figure 1 shows a graphical representation of the whole mechanical simulator.

Tests have been made by acquiring simultaneously the reference velocity signal and the video for 30 seconds. This procedure has been repeated changing the rotation velocity of the plate.

The reference velocities measured by the light emitter-detector device and the trajectories of dummy’s points, estimated through the two motion estimation techniques have then been compared.

3. DATA ANALYSIS

The reference signal has been processed to obtain the angular velocity, in rounds per minutes (RPM).

The motion estimation techniques has been used by choosing points on the dummy whose distance from the rotating centre was known. The trajectories of these points have been estimated and subsequently point positions and angular velocities have been evaluated over time.

Many techniques are generally used for motion estimation (e.g. Block Matching, Optical Flow, Transformed Domains [15,16,18]). The Roma TRE research group has proposed some innovative approaches for a markerless motion analysis: an improved Block Matching Algorithm (as in [12]), and a Transformed Domain approach (as in [14], [2]) based on the Laguerre Gauss expansion.

The first step is the estimation of the integer translation \( \mathbf{d}_{INT}^T(t) \) through the minimization of an integral cost function throughout an evaluation area \( W \):

\[
\mathbf{d}_{INT}^T(t) = \arg \min_{\mathbf{d} \in A} CF(d,t)
\]  

where:

\[
CF(d,t) = \sum_{z \in W} \left| I(r + z/\Delta t) - I(r - d,t) \right|_{R,G,B}
\]  

and \( I(t + \Delta t) \) and \( I(t - d,t) \) are the consecutive frames analysed and \( r \) and \( r - d \) are the positions of the chosen point and \( A \) represents the area of research.

The Euclidean distance with no weight functions was chosen as a distance measure.

The second step estimates the fractional translation \( \mathbf{d}_{SUB}^T(t) \), by finding the location of the minimum of the spline interpolation function, \( CF_{SUB}(d,t) \) obtained using the neighbouring pixels as nodes.

The application of Block Matching Algorithm allows to estimate trajectories of points of interest comparing the luminance component of consecutive frames.

The second motion estimation method is based on the Laguerre Gauss expansion (LG). This technique analyses each frame with a transformed domain approach using the Wavelet transformation. The image is transformed with a series expansion finding a sum of primitive images that present the different characteristics of the original image (like lines, edges, crosses). If \( I(r) \) is the original image, \( W_{S}(a,b) \) is the Wavelet transform of \( I(r) \) and it’s written as:

\[
W_{S}(a,b) = \langle I(r), \Psi_{a,b} \rangle = \frac{1}{\sqrt{a}} \int I(r) \cdot \Psi_a \left( \frac{r - b}{a} \right) \, dr
\]

where \( a \) and \( b \) are complex factors (scale and translation factors respectively) and \( \Psi^* \) is the Mother Wavelet.

In the Laguerre Gauss expansion, the Mother Wavelet, used to transform the signal is the Circular Harmonic Function of Laguerre Gauss, with the following form:

\[
L_k^{(n)}(r, \theta) = (-1)^k 2^n k! k^{n/2} \pi^{1/2} \left( \frac{k!}{(n+k)!} \right)^{1/2} \cdot r^n L_k^{(n)}(2r^2) e^{-\pi r^2} e^{i\theta}
\]

where \( L_k^{(n)} \) are the Laguerre Polynomial with order \( n \) and degree \( k \).

The Laguerre Gauss expansion allows to examine each frame in a transformed domain where the image characteristics are separated in different planes. It’s possible to estimate the position of a chosen point over time by means of a Maximum Likelihood (ML) Estimation between consecutive transformed frames.
The two techniques have been tested through the analysis of the dummy on the rotating plate. The estimated kinematics of the tracked elements has been evaluated in terms of Root Mean Square Error (RMSE) with respect to the nominal kinematics as reconstructed through the velocity detector, in two different conditions: at first by tracking selected regions on the dummy surface, and then by tracking markers applied on the dummy.

4. RESULTS

Results have been obtained by testing the BMI algorithm and LG algorithm. The results refer to two different plate rotating velocities, evaluated for every test.

In every trial, the velocity has been evaluated considering the signal position obtained through the photodetector. This value has been compared with the velocity obtained from the analysis of the trajectories achieved with motion estimation techniques.

In table I and II the results, obtained by analysing a point with a marker on, are shown. The results obtained with both BMI and LG algorithms are compared.

Table I refers to velocity analysis considering the same points for the two types of motion estimation analysis. For every test the rotation velocity has been measured and a comparison with the two estimated velocities has been carried on, obtaining the percent error rate (% error).

\[
\text{TABLE I} \\
\begin{array}{|c|c|c|c|}
\hline
\text{Test} & \text{Detected Velocity (RPM)} & \text{Marker Estimated Velocity (% error)} \\
\hline
\text{video1} & 36.47 & 1.75 & 4.98 \\
\text{video2} & 29.53 & 1.04 & 4.82 \\
\hline
\end{array}
\]

Table II refers to trajectory analysis obtained considering the same points for the two type of motion estimation analysis. The real trajectories have been evaluated as in the case with markers and compared with the estimated trajectories in order to calculate RMSE.

\[
\text{TABLE II} \\
\begin{array}{|c|c|c|}
\hline
\text{Test} & \text{BMI} & \text{LG} \\
\hline
\text{video1} & 0.355 & 0.479 \\
\text{video2} & 0.227 & 0.340 \\
\hline
\end{array}
\]

In table III and IV the results, obtained analysing a point on a surface body region, are shown. The results obtained with both BMI and LG algorithms are compared too.

Table III refers to velocity analysis considering different points with respect to the previous case. For every test the rotation velocity has been measured and compared to two estimated velocities, obtaining the percent error rate (% error).

\[
\text{TABLE III} \\
\begin{array}{|c|c|c|c|}
\hline
\text{Test} & \text{Detected Velocity (RPM)} & \text{Markerless Estimated Velocity (% error)} \\
\hline
\text{video1} & 36.47 & 3.23 & 0.26 \\
\text{video2} & 29.53 & 0.17 & 3.78 \\
\hline
\end{array}
\]

Table IV refers to trajectory analysis obtained considering the same points for the two type of motion estimation analysis. The real trajectories have been evaluated as in the case with markers and compared with the estimated trajectories in order to calculate RMSE.

\[
\text{TABLE IV} \\
\begin{array}{|c|c|c|}
\hline
\text{Test} & \text{BMI} & \text{LG} \\
\hline
\text{video1} & 1.54 & 1.05 \\
\text{video2} & 0.56 & 0.72 \\
\hline
\end{array}
\]

In figure 2 the motion estimation results are shown through a polar diagram for both marker and markerless cases. Each of the two diagrams represents the estimated trajectory of the point while the plate is rotating. The results are those obtained with the Block Matching Algorithm. The ideal trajectory is also reported for comparison purpose.
5. DISCUSSION

The obtained results show that the error on the velocities is less than 5\% in the estimation of the marker trajectories (Table I). In this case the BMI algorithm has better performances than LG algorithm. It depends on the nature of the used algorithms: the marker presents a level of luminance distinguishable from the background and, for this reason, the BMI method, based on the tracking of points with the same luminance values, “follows” the initial point with better accuracy.

Considering the same videos and points, the RMSE obtained with BMI algorithm is lower than in the LG analysis (Table II). This is due to the same reasons explained for the previous velocity analysis.

The marker results depend on the chosen velocity: lower velocities corresponds to lower errors.

In the estimation of the markerless trajectories, the obtained results show that the error on the velocities is less than 4\% (Table III). In this case both algorithms present similar performance in terms of velocity estimation.

The RMSE for markerless estimated trajectories is higher than for the marker case using both algorithm, as it was expected (Table IV). Errors, in any case, are less than 1.6 cm so the tested markerless systems present levels of accuracy adequate for future applications on human motion analysis.

6. CONCLUSIONS

The proposed method uses mechanical simulator to evaluate the accuracy of motion estimation algorithms both with and without markers. The results obtained with the examined techniques are encouraging and the possibility of developing more complex motion estimation techniques can hopefully enhance the accuracy.

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