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COMBINING OPTICAL MARKERS AND INERTIAL SENSORS WITHIN AN EXTENDED KALMAN FILTER FOR REAL-TIME HUMAN MOTION CAPTURE

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INTRODUCTION

The two most widespread technologies currently used to capture human motion in biomechanical applications are marker-based optical systems and inertial measurement units (IMUs).

Optical motion capture is still regarded as the most accurate method, so its results are often used as a baseline to assess the performance of other techniques, including the inertial systems mentioned above [1]. However, it is not always the most convenient solution, as it requires a relatively complex and expensive setup, it is limited to a specific capture space, and marker occlusions impair its robustness. In addition, when the captured motion is used to estimate the joint torques from inverse dynamics, velocities and accelerations have to be calculated by numerical differentiation, and this implies a previous filtering process whose parameters are not always easy to determine [2, 3].

Inertial systems, on the other hand, are usually more cost-effective and portable than optical ones. Moreover, they are much less prone to data interruption issues, which makes them more robust. Their main drawbacks are the position drift and the difficulty to estimate the orientation accurately when the movement involves large accelerations.

There already exist some methods that seek to combine the positional accuracy of optical systems and the robustness and convenience of inertial ones [4, 5]. However, they treat each IMU as a self-contained device that computes its own absolute orientation by using an on-board sensor fusion algorithm. The problem about this approach is that the accelerometers are just employed as a reference for the direction of gravity, regarding the accelerations due to movement as sensor noise, which is the main cause of the inaccuracies mentioned above.

In this work, an extended Kalman filter (EKF) that combines optical markers and inertial sensors in a fully integrated way is presented. The method aims to enhance the robustness of optical motion capture against marker loss, while providing a more accurate estimation of the joint torques, thanks to the addition of direct measurements of angular velocity and acceleration.

METHODS

The proposed EKF is an extension to that presented in [3] and [6]. In this case, along with the optical markers, a set of IMUs is attached to the body segments, as shown in Fig. 1.

Fig 1: 3D model with optical markers and IMUs.

As done in [6], the state vector $\mathbf{x}$ contains the independent positions $\mathbf{z}$, velocities $\dot{\mathbf{z}}$ and accelerations $\ddot{\mathbf{z}}$ of the model. The observation function $\mathbf{h}(\mathbf{x})$, which, in the previous algorithm, provided the absolute 3D coordinates of the optical markers as a function of $\mathbf{z}$, is now augmented by adding the virtual gyroscope and accelerometer readings, $\bar{\bar{\boldsymbol{\omega}}}_s$ and $\bar{\bar{\mathbf{a}}}_s$. These magnitudes are defined in the local frame of reference of the corresponding sensor so, in order to express them as a function of the system states $\mathbf{x}$, it is necessary to determine the relative position $\bar{\mathbf{r}}_s$ and orientation $\bar{\mathbf{A}}_s$ of each IMU within the local frame of the body segment i it is attached to.

The local coordinates of the IMUs are considered constant, and they can be estimated in a preliminary calibration step, by measuring the positions and orientations of all the body segments and inertial sensors while the subject remains in a static pose, and then calculating the difference. However, it should be noted that,

although IMUs can estimate their own orientation quite accurately in static conditions, they are not able to provide position information, so it is necessary to place optical markers or clusters on them. Once the positions $\bar{\mathbf{r}}_s$ and orientations $\bar{\mathbf{A}}_s$ of the IMUs within their corresponding body segments are established, the virtual sensor measurements can then be expressed as a function of the state vector $\mathbf{x}$.

The angular velocity of body i in its own local axes can be written as the product of a position-dependent matrix $\bar{\mathbf{W}}_i$ and the time derivatives of the corresponding Euler angles $\dot{\mathbf{z}}_i$:

$$\bar{\boldsymbol{\omega}}_i = \bar{\mathbf{W}}_i \dot{\mathbf{z}}_i$$

Since both body segment i and its attached sensor s have the same angular velocity, the virtual gyroscope measurement can be obtained by just rotating the previous expression to the IMU frame:

$$\bar{\bar{\boldsymbol{\omega}}}_s = \bar{\mathbf{A}}_s^{\mathrm{T}} \bar{\mathbf{W}}_i \dot{\mathbf{z}}_i$$

The accelerometer measurement is derived from its absolute acceleration $\ddot{\mathbf{r}}_s$:

$$\ddot{\mathbf{r}}_s = \ddot{\mathbf{r}}_i + \ddot{\mathbf{A}}_i \bar{\mathbf{r}}_s$$

where $\mathbf{r}_i$ is the position of the origin of body i, and $\mathbf{A}_i$ is its orientation matrix. By adding the acceleration of gravity $\mathbf{g}$ to this expression, then transforming the result to the local axes of body i, and rotating it again to the local frame of the IMU, the accelerometer measurement can be expressed as a function of the states as follows:

$$\bar{\bar{\mathbf{a}}}_s = \bar{\mathbf{A}}_s^{\mathrm{T}} \mathbf{A}_i^{\mathrm{T}} \left(\ddot{\mathbf{r}}_i + \ddot{\mathbf{A}}_i \bar{\mathbf{r}}_s + \mathbf{g} \right)$$

Adding these sensors to the observation function enables the EKF to take advantage of all the sensor measurements in a completely integrated way, with the accelerations due to the estimated motion automatically separated from gravity.

A simpler version of the filter using only gyroscopes is also studied. This solution is simpler to implement, since the Jacobian matrix of the observation function is considerably simplified and, in addition, the absence of accelerometers makes placing markers on the IMUs unnecessary. Although removing the accelerometers may degrade the estimation of joint torques, the addition of gyroscopes is still an enhancement over using optical markers alone, and the improved robustness against marker occlusions is not lost.

RESULTS AND DISCUSSION

Directly integrating a set of inertial sensors to the EKF leads to a number of benefits. Firstly, the motion reconstruction becomes much more robust against marker occlusions. Secondly, it is possible to obtain accurate and delay-free accelerations in real time, which lead to better joint torque estimations [6]. Finally, adding IMUs can also improve the portability of optical systems, as it allows drift-free full-body motion capture with a minimal set of optical markers, which would require fewer cameras.

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