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Short communication

Mobile platform for motion capture of locomotion over long distances

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ABSTRACT

Motion capture is usually performed on only a few steps of over-ground locomotion, limited by the finite sensing volume of most capture systems. This makes it difficult to evaluate walking over longer distances, or in a natural environment outside the laboratory. Here we show that motion capture may be performed relative to a mobile platform, such as a wheeled cart that is moved with the walking subject. To determine the person's absolute displacement in space, the cart's own motion must be localized. We present three localization methods and evaluate their performance. The first detects cart motion solely from the relative motion of the subject's feet during walking. The others use sensed motion of the cart's wheels to perform odometry, with and without an additional gyroscope to enhance sensitivity to turning about the vertical axis. We show that such methods are practical to implement, and with present-day sensors can yield accuracy of better than 1% over arbitrary distances.

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1. Introduction

Motion capture of human locomotion is usually limited to a finite space, whose volume is defined by a set of fixed cameras or other sensors. This makes it difficult to characterize some activities, such as unsteady or unconstrained walking. Treadmills function well for steady, continuous walking, but not for significant changes in speed or direction. Motion captured over-ground for large distances could facilitate the study of a greater range of activities than currently possible.

An alternative is to fix the sensors to a wheeled cart that is moved to accompany the human subject. This allows for measurement of the subject's motion relative to the ground, if the cart's absolute displacement can be estimated. For human walking, one such indicator of cart motion is the relative position of foot-mounted motion capture markers. Assuming that there is always one foot at rest on the ground, at least one marker will indicate cart motion (Bauby and Kuo, 2000). An alternative is to use odometry, referring to path integration of the cart's velocity as sensed from its wheels (Kelly, 2004). We previously used a combination of these methods to measure step variability (Bauby and Kuo, 2000), and could capture 100 or more contiguous steps during straight walking. Changes in walking direction can, however, reduce accuracy due to slippage between between feet or wheels with ground. Fortunately, adding a gyroscope can correct for such issues (Chung et al., 2001).

The methods above are standard in the field of mobile robots, but are subject to trade-offs in performance and complexity. They have yet to be assessed in the context of human motion capture. In the present study, we have implemented and tested all three methods: foot-based sensing, wheel-only odometry, and gyroscope-enhanced odometry. We also present techniques for quantifying accuracy and offer suggestions for addressing common practical issues. This may facilitate motion capture over distances longer than practical in the laboratory.

2. Methods

We implemented three methods of long-distance motion capture, and tested them for overground walking. The hardware consisted of a cart-mounted motion capture system for sensing the person in three dimensions, and optical encoders and a gyroscope for sensing the motion of the cart (see Fig. 1). We first present the foot-referenced method, which was assessed along straight-line walking. This is followed by two odometry methods, one based on sensing of the cart's wheels, and the other adding a gyroscope for yaw rotation. Details regarding sensors and methodology can be found in Supplementary material A.

2.1. Foot-referenced estimation of cart motion

Motion of the cart may be determined solely from the relative motion of foot-mounted markers. During walking, the stance legs alternate, so that at least one foot is stationary on the ground at all times (Bauby and Kuo, 2000). One of the principal challenges is to identify which marker is stationary on the ground, based on markers alone. During walk, we assume that each foot is always either stationary or moving only forward in space. If the cart moves forward, a foot on the ground will have a marker moving backwards relative to the cart. Therefore the marker with most rearward velocity therefore indicates which foot is stationary.

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Nomenclature

T	sampling period
L	traveled distance
d_l, d_r	left and right foot displacement relative to cart, measured with motion capture system
v	estimated foot-referenced cart speed
D	wheel diameter
C	encoder count-per-revolution parameter
B	cart wheel separation or base
e_l, e_r	left and right wheel encoder outputs
s_l, s_r	left and right wheel displacement
x, y	cart position relative to the origin
x_e, y_e	cart return positioning error
$\overline{x}_e$	average forward percentage error
ψ	cart heading angle
ψ_e	cart return heading error
$\overline{\psi}_e$	average of the absolute return heading error
ω	gyroscope output
d_e	return distance error
$\overline{d}_e$	average position percentage error

Two main limitations of this method are that it does not capture changes in cart heading, and is not suitable for running gaits. This method is termed Leap-Frog localization (Tully et al., 2009) in cooperative robotic applications, referring to alternation between stationary reference points.

This method is highly dependent on marker placement on the foot. For optical motion capture, it was necessary to mount markers on the heels of the feet for line of sight. These locations are challenging to track because the heel comes to rest very briefly during each step, and heelstrike induces vibrations of the foot, shoe, and marker. An alternative is to use magnetism-based markers that do not require line of sight (e.g., Ascension Technologies, Inc.; Burlington, VT.), mounted atop the foot insteps (Bauby and Kuo, 2000). That location is relatively motionless during much of the stance.

The cart speed can be estimated from the displacement of whichever foot is stationary. Given a sequence of forward displacements for the left and right feet (d_l and d_r, respectively), the cart forward speed v can be computed as the difference between two consecutive measurements, using whichever foot shows the smaller motion in the moving capture frame

$$v(n) = \begin{cases} -\frac{d_l(n)-d_l(n-1)}{T}, & \text{if } d_l(n)-d_l(n-1) \le d_r(n)-d_r(n-1) \\ -\frac{d_r(n)-d_r(n-1)}{T}, & \text{if } d_l(n)-d_l(n-1) > d_r(n)-d_r(n-1) \end{cases} \qquad (1)$$

where T is the sample period. Cart speed v has opposite sign to the marker displacements, which are moving backwards relative to the cart, hence the negative sign in the Eq. (1). A similar equation may be applied for backward cart motion. The x-direction is defined as forward for the cart, and the y-lateral direction is not measured (Fig. 1). Forward position is updated according to

$$x(n+1) = x(n) + v(n)T \qquad (2)$$

The estimated cart speed can be corrupted by missing or occluded marker data. We address this problem by filtering the cart speed using a Kalman filter (see Supplementary material B for details).

2.2. Wheel-based odometry

We also implemented an estimate of the cart's motion from wheel encoders. This method does not depend on the nature of the subject's footsteps, and therefore applies even when the feet slip on the ground or have an aerial phase. Here, the primary assumption is that the wheels roll a fixed distance per revolution, without slipping on the ground. This is a form of dead-reckoning, based on the integral of wheel motion.

We measured wheel rotation with optical encoders located on the rear wheels of the cart. The encoder count change during a sample periods e_l and e_r, can be translated into left and right wheel forward displacements (s_l and s_r, respectively), using information about wheel diameter D and the count-per-revolution C specification of the encoders

$$\begin{bmatrix} s_l(n) \\ s_r(n) \end{bmatrix} = \begin{bmatrix} e_l(n) \\ e_r(n) \end{bmatrix} \frac{\pi D}{C} \qquad (3)$$

These data may be used to track cart motion in the ground plane. Given a separation between wheels B and the wheel linear displacement, the cart displacement (x forward, y lateral, and ψ yaw rotation or heading, defined relative to an initial configuration) is updated according to

$$\begin{bmatrix} x(n+1) \\ y(n+1) \\ \psi(n+1) \end{bmatrix} = \begin{bmatrix} x(n) \\ y(n) \\ \psi(n) \end{bmatrix} + \begin{bmatrix} \frac{s_r(n)+s_l(n)}{2} \cos\left(\psi(n) + \frac{s_r(n)-s_l(n)}{2B}\right) \\ \frac{s_r(n)+s_l(n)}{2} \sin\left(\psi(n) + \frac{s_r(n)-s_l(n)}{2B}\right) \\ \frac{s_r(n)-s_l(n)}{B} \end{bmatrix} \qquad (4)$$

Additional details can be found in Supplementary material C.

2.3. Gyroscope enhanced odometry

For conditions such as walking around corners, the cart's yaw rotation may be estimated more accurately with a gyroscope, which senses angular velocity without being affected by external conditions. We integrate the gyro sensor output ω over time to estimate relative cart heading (with respect to the starting pose). Position and heading are computed as

$$\begin{bmatrix} x(n+1) \\ y(n+1) \\ \psi(n+1) \end{bmatrix} = \begin{bmatrix} x(n) \\ y(n) \\ \psi(n) \end{bmatrix} + \begin{bmatrix} \frac{s_r(n)+s_l(n)}{2} \cos\left(\psi(n) + \frac{\omega(n)T}{2}\right) \\ \frac{s_r(n)+s_l(n)}{2} \sin\left(\psi(n) + \frac{\omega(n)T}{2}\right) \\ \omega(n)T \end{bmatrix} \qquad (5)$$

The heading estimate from the gyroscope could be improved by fusing it with encoder data using estimation techniques (i.e. Kalman filters). However, the benefits are minimal when using a low-drift and well-calibrated gyroscope as in our case (Chung et al., 2001), and as discussed previously by others (Ojeda et al., 2000).

3. Experimental results

For the foot-referenced method, we measured straight-line walking and evaluated the forward displacement errors for a foot-mounted marker. We performed 20 straight walk experiments ($N=20$), each at a known distance of 20 m ($L=20$). The average error $\overline{x}_e$ (Eq. (6)) for our implementation of foot-referencing was 3.8%, which was reduced to 2.7% with the digital

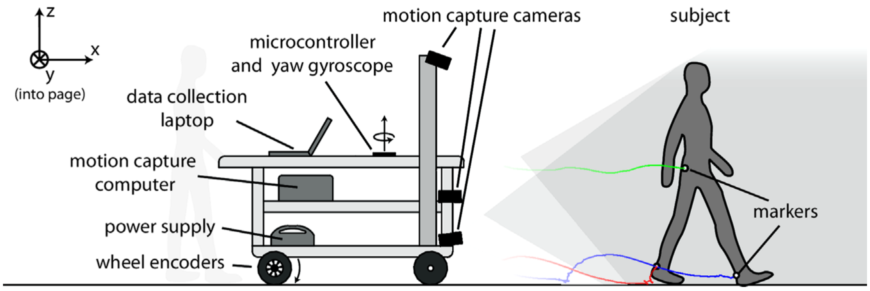

Fig. 1. System for collecting overground walking data. Motion capture cart is pushed behind the walking subject, recording marker paths relative to the cart. On-board sensors (encoders and gyro) and 3-dimensional marker data are then used to determine marker paths relative to ground.

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