1 Introduction

Feedback control for robots relies on accurate estimates of the joint state. Traditionally, the joint position is measured using an angular sensor from which joint derivatives are computed numerically. This amplifies noise, requiring low-pass filtering for use in control. However, filtering introduces a delay; preventing the use of feedback gains high enough for satisfactory stiffness and damping. We have developed methods [1] for computing joint velocity and acceleration from inertial sensors which measure quantities of the same order. These estimates - from gyroscopes and accelerometers - can be used for higher-performance robot control and potentially even for determining the joint state of a human subject.

2 Approach

While various inertial sensors have been used in sensor fusion for decades, research on robot joint state estimation using these sensors has been limited [2], [3], [4], [5]. We develop a method for computing the velocities of general three-degree of freedom joints of a serial chain attached to a floating base. Using additional knowledge of the robot’s kinematics, we can further constrain joint velocities to the structure of the actual system. While these methods assume the orientation of each IMU with respect to the link frame, we additionally develop offline calibration methods to account for imprecise sensor placement. Likewise, we develop a method for determining joint accelerations from computed joint velocities and measured IMU accelerations. This requires no knowledge about the global state of the sensor. Again, we detail a calibration procedure to automatically determine sensor positions with respect to their link frames.

These geometry-based computations form the basis for sensor fusion approaches which allow estimation of gyroscope biases as well as filtered joint positions and velocities through the use of joint accelerations in a forward model. We ultimately demonstrate the utility of computing joint derivatives from inertial sensors by implementing a joint proportional-derivative (PD) controller using gyroscope-based velocities.

3 Results

Joint velocities from link-mounted IMU gyroscopes were computed and compared to filtered potentiometer-based velocities which serve as a delayed but accurate form of ground-truth. Figure 2 demonstrates the effect of using the offline orientation calibration routine to correct for imprecise sensor-link frame alignment.

Joint accelerations computed from potentiometer measurements are of very poor quality; on the other hand, Figure 3 shows joint accelerations computed from inertial sensors, both using manually-measured IMU positions and with those automatically calibrated using our offline routine. Both match the heavily-filtered potentiometer-based accelerations well with less delay.

We obtained much more stable joint PD control when using gyroscope-based joint velocities versus filtered, differentiated potentiometer signals which are subject to delay. Figure 4 demonstrates that damping is considerably improved for the same gains when using the gyroscope-based velocities. Further, we were able to increase the maximum stable proportional gain by 50% when using these velocities, resulting in significantly better tracking.

Figure 1: Inertial Measurement Units (IMUs) attached to the thigh, shank and foot of a SARCOS hydraulic humanoid.
4 Outlook

Although we were able to demonstrate the utility of IMU-based joint velocities for single joint PD control, we are working to fuse these velocities with model-based accelerations in order to filter the computed joint velocities with minimal delay. We intend to use the resulting joint state estimates for full-state feedback with gains derived from Linear Quadratic Regulator (LQR) control design [6]. It is expected that the use of filtered, gyroscope-based joint velocities will significantly improve LQR performance due to the ability to increase gains and obtain better damping characteristics. We have found that damping is crucial to success in our walking experiments both with decoupled (joint PD) and coupled (LQR) controllers as higher gains are necessary to obtain good center of mass tracking.

References


