Joint velocity measurement using low-cost high bandwidth MEMS gyroscopes.

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In our control framework, the Instantaneous Capture Point (iCP) is at the core of the balance control. It allows the walking algorithm to plan the robot center of mass trajectory over the upcoming steps to take. In addition to planning, the iCP state is controlled at all time to track a desired state ensuring stability and robustness. However, to enable good feedback control, the actual measurement of the iCP has to be accurate [1].

In order to accurately predict the iCP of a humanoid robot it is necessary to have high speed precise joint velocity measurements. Balance controllers using the iCP to actively balance generally run at a frequency of 500 Hz to a 1000 Hz.

High resolution rotary or linear position encoders that can provide an update rate of at least 1000 Hz are relatively low cost and generally available. By differentiating the position values, an estimate of the velocity can be made. However, due to mechanical design constraints it is not always feasible to place the joint encoder directly on the output axis of the joint. Any backlash or elasticity in the transmission between the location position measurement and the joint output will be visible in the position signal. This can result in large spikes in the differentiated velocity signal. This effect is especially visible when the joints are effectively stationary but the input actuator is fighting to compensate for backlash and elasticity.

The traditional method of compensating for the velocity spikes is a low pass filter, but reducing the break frequency of the low pass filter will result in reduced bandwidth of the system.

Low cost MEMS gyroscopes provide three axis velocity measurements with respect to their own inertial frame. By using two gyros, one on the input link and one of the output link of a joint, we can use their relative velocity measurements to estimate the joint velocities. If multiple joints are between two gyros, we can use a a state estimator framework to improve the measured signals.

As long as a joint is limited in its maximum rotation, we can assume that the average joint velocity is zero over a sufficiently long period of time. By using a very low frequency low pass filter we can estimate the velocity bias of the MEMS gyro velocity using only its own velocity measurements.

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[1] Koolen, Twan, Sylvain Bertrand, Gray Thomas, Tomas De Boer, Tingfan Wu, Jesper Smith, Johannes Englsberger, and Jerry Pratt. "Design of a momentum-based control framework and application to the humanoid robot atlas." *International Journal of Humanoid Robotics* 13, no. 01, 2016, 1650007.

We developed a low cost high bandwidth MEMS gyro interface board using off the shelf components. As gyro we used the Invensens MPU6000 IMU[2]. To provide sufficient bandwidth to the control computer, we used the EtherCAT[3] communication protocol. EtherCAT has the concept of distributed clocks, which allow all slaves to synchronize their internal clock within a few hundred nanoseconds. Internally, the EtherCAT slaves can generate a periodic interrupt to start a measurement. This allows all EtherCAT slaves to start a measurement at approximately the same moment in time. EtherCAT has a very low overhead and small forwarding delays. Assuming a single 32 bit floating point value per gyro axis, we can run approximately 500 slaves at 1Khz[4]. A prototype can be seen in figure 1.

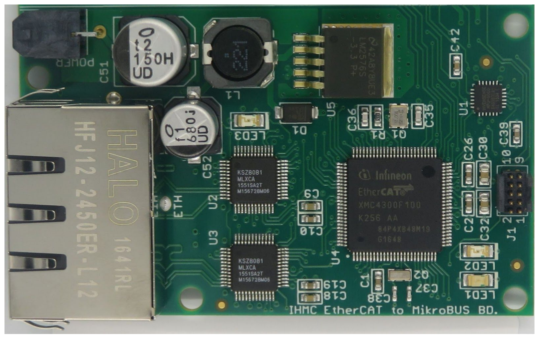

Figure 1: IHMC Low Cost Gyro prototype

We integrated a prototype of this gyroscope in the chest of the Atlas robot. The Atlas robot has three spine joints between the pelvis and the chest. The spine joints use a pushrod for actuation which results in a large amount of backlash. Using the low-cost MEMS gyro on the chest in conjunction with the built-in IMU in the pelvis we can get improved velocity measurements for the spine joints.

Further work will include fabricating a larger number of gyroscopes to attach on every major link of the Atlas body. The improved joint velocity estimates will result in a better iCP estimate as well as to allow us to increase the gains inside the controller without instabilities due to bad measurements and noise[5]. In turn, this will allow us to do more dynamic behaviors. When using multiple EtherCAT connected gyros we expect the synchronized measurements to improve the accuracy of our measured signals.

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[2] Invensens, “MPU-6000 and MPU-6050 Product Specification Revision 3.4”, https://www.invensense.com, 2017.
[3] D. Jansen and H. Buttner. "Real-time Ethernet: the EtherCAT solution." *Computing and Control Engineering* 15, no. 1, 2004, pp. 16-21.
[4] Prytz, Gunnar. "A performance analysis of EtherCAT and PROFINET IRT." In *Emerging Technologies and Factory Automation, 2008. ETFA 2008. IEEE International Conference on*, pp. 408-415. IEEE, 2008.
[5] Xinjilefu, X., Siyuan Feng, and Christopher G. Atkeson. "A distributed mems gyro network for joint velocity estimation." In *Robotics and Automation (ICRA), 2016 IEEE International Conference on*, pp. 1879-1884. IEEE, 2016.

Abstract: To improve joint velocity measurements, we developed a low cost high bandwidth gyro interface board with an EtherCAT interface. Our gyro allows us to take simultaneous measurements of the angular velocity of up to 500 links and use the difference between those measurements to estimate the joint velocities. A prototype interface board has been installed in the Atlas robot and significantly improves the spine joint velocity estimate.

Technical presentation by the author: https://youtu.be/nwcJrfPhc4w