Real World Issues with Real-Time Control of MABEL:

A Platform for Experimental Control of Bipedal Locomotion

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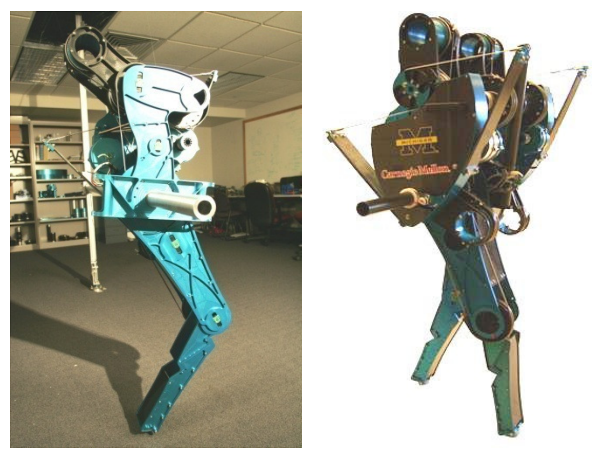
***Abstract*—This paper describes selected issues with the commissioning and implementation of a real-time control system for an experimental bipedal robot platform named MABEL at the University of Michigan. Real world issues with printed circuit board layout and manufacturing, replacement of third party components, and communication issues associated with the computer control system are discussed. Control system implementation issues such as cable stretching in the hip and knee joint drivetrains, sensor resolution issues, and problems with software implementation related to computer processing speed for control system throughput are also presented. We illustrate solutions to each of these specific issues. In addition to standard troubleshooting processes, several complex concepts that may aid any commissioning and implementation effort are noted. A summary and discussion of future work with the robot conclude the paper.**

Keywords-Bipedal robot, real-time control, troubleshooting, sensor resolution

I. INTRODUCTION

Since the conception of humanoid robots, there has been significant experimentation and success in the field of robotic bipedal locomotion. In the fall of 2004, a multidisciplinary collaborative effort between the Robotics Institute of Carnegie Mellon University and the University of Michigan Ann Arbor began to specify, design, manufacture, and implement two types of experimental platforms for legged robotic motion with the unique feature of compliance: a spring system to store impact energy and return it back to the gait instead of drawing additional energy from the system. A single leg "hopper" named Thumper (see Figure 1 (a)) was successfully implemented at Carnegie Mellon. A bipedal version of the hopper, named MABEL (see Figure 1 (b)), was created by mirroring the design of the one hopper leg and connecting it to a second leg at the hip joint. As a platform for the study of two-dimensional bipedal locomotion in robots, MABEL is restricted to movement in a circle around a center boom, as illustrated in Figure 4. MABEL has been successfully implemented by a team at the University of Michigan. While the conception, specification, and design phases of the projects are well documented in [1], [2], [3], [4], and [5], this paper details some of the real world issues with real-time control of MABEL. A brief introduction to the system hardware and software is provided, followed by a detailed list of problems that were overcome during the commissioning and implementation of the real-time control system.



(a) (b)

Figure 1: (a) Thumper (b) MABEL

II. HARDWARE AND SOFTWARE

Implementation of the real-time control system requires joint actuation and position sensing for estimating the robot pose in space and for performing feedback control. As shown in Figure 2, the Real-time Control System Block Diagram, 15 encoders are used: 6 per leg, 2 for the boom (X and Y) and 1 for the torso angle. In addition, each joint is equipped with multiple limit switches to detect motion past the full range of travel. Laser displacement sensors were added for evaluating the possibility of obtaining high accuracy measurements of the torso angle and boom height, and for potential use in detecting obstacles. All encoders, limit switches, and laser displacement sensors report to a QNX real-time control computer chassis

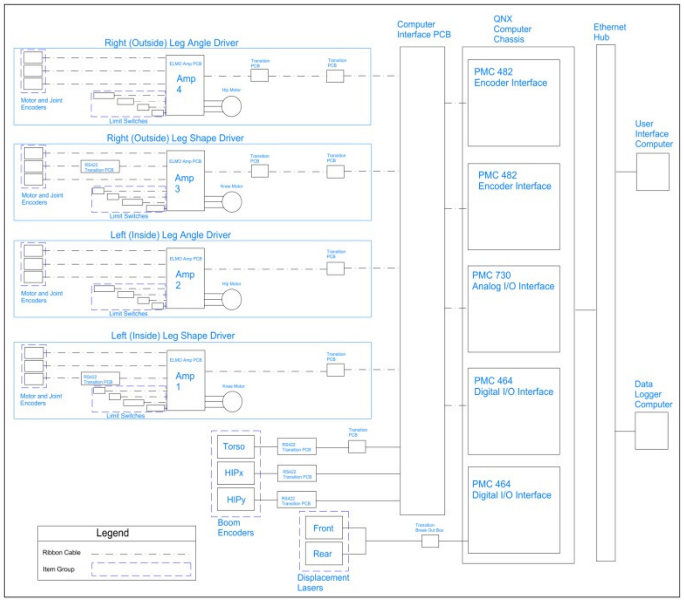


Figure 2: Real-time Control System Block Diagram.

through selected Acromag data acquisition (DAQ) boards. The QNX system communicates to separate user interface and data logging computers via an ethernet hub. Elmo Motion Control high power DC to three-phase AC motor amplifiers are used to actuate joint movement. The amplifiers receive control system commands from an Acromag output board via a transition computer interface circuit board. This circuit board also establishes necessary connections between the joint encoders and limit switches, as well as the boom and torso encoders. Note that both the knee and hip joint motors actuate the joints via cable differentials, not as direct drivers.

MABEL uses a QNX real-time computing and DAQ environment to acquire data from sensors, compute control action, and output commands to actuators, all at a rate of 1KHz. The software framework for the control system implementation is based on RHexLib, a system architecture originally developed for the RHex running robot [6]. RHexLib is a collection of software libraries that facilitates implementation of real-time controllers, switching of controller modules, over-the-network data logging, handling communication with the robot, and provides a user-interface for monitoring the robot state on a secondary Linux based system.

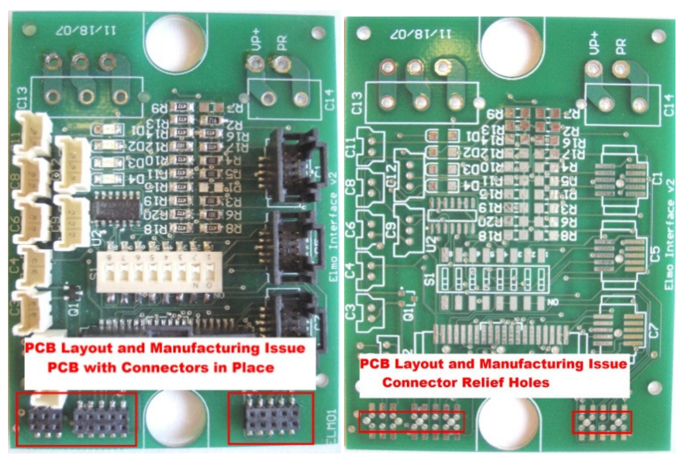
III. Real World Issues

With any system designed and specified from a "clean sheet," there are typically a number of commissioning, implementation and real-time control system issues to be overcome. Getting MABEL "up and walking" presented issues in each of the following categories: first, commissioning issues related to printed circuit board layout and manufacturing and replacement of third party components; second, completing the necessary connections for proper and noiseless or "clean" system communications; third, a control system issue with cable stretch in the joint differential system; fourth, implementation issues based on the sensing resolution requirements to deliver accurate real-time control; and fifth, a software issue related to the processing speed necessary to maintain proper throughput for real-time control.

A. PCB Layout and Manufacturing Issue

Initial commissioning of any complex system is often simplified by breaking the system up into pieces or subsystems allowing testing of smaller less complex sections prior to attempting to run the entire system. In this sense, MABEL was no different. Bench tests were specified to assure that the DC to three phase AC motor drive system operated as expected when controlled via the QNX system. Since the on-board amplifier control printed circuit boards (pcb) were specified, designed, and manufactured expressly for this project, this decision proved wise. While typical pcb issues with newly designed circuit boards such as layout misinterpretation, mispopulated components, and missed or shorted solder connections, were quickly remedied, one issue proved more difficult to diagnose.

A communication problem between the amplifier control pcbs and QNX chassis persisted through the standard trouble shooting methods. A short circuit was noted at a few of the surface mount connectors between the two systems on some component populated boards (see Figure 3 (a)) and not on others; additionally, the short circuit would exist between different sets of pins on the boards that exhibited the problem. When the connectors were removed from the boards and checked for shorts, the connectors themselves operated as expected revealing no internal shorts. Also, when the boards were removed from the amplifiers, the amplifiers revealed no shorts. So, the problem *only* occurred when the connectors were installed on the pcbs and the pcbs were installed on the amplifiers.



(a) (b)

Figure 3: PCB Layout and Manufacturing Photos, with (a) connectors in place, and (b) without connectors, depicting the connector relief holes.

After a lengthy visual inspection of an unpopulated amplifier pcb, it was noted that the holes specified for allowing the amplifier pins to enter the connector from the bottom side of the pcb were not actually mounting holes for the connector, but merely relief holes to allow the amplifier pins to pass through the pcb and enter the connector from below. Since the holes are not used for mounting or electrical connection, but were only specified as a "through hole" for connector to pin access for the amplifier to connect to the pcb, they did not need to be plated. Although the holes were large enough to accommodate the intended function (see the unpopulated pcb in Figure 3 (b)), the holes were plated just like any standard via or hole as part of the pcb manufacturing process. So, when the pcb was seated on the amplifier, the pins entered the bottom of the board and exited the top of the board and into the connector. On the way though the board some pins would touch the relief hole plating leading to short circuits between the pins. Again, this occurred *only* when the connectors were mounted *and* the pcb was seated on an amplifier. Using an electric rotary tool, the offending plating on the relief holes was machined away and the problem was solved. A brief history and concise summary of the printed circuit board manufacturing process is available on the website of Advanced Circuits, Inc. [7]

B. *Third Party Amplifier Manufacturing Issue*

Another manufacturing issue arose with the third party designed and manufactured amplifiers, when two of the Elmo Motion Control amplifiers were damaged by an over current condition during an early experiment. The amplifiers are a "black box" component in MABEL's design. They convert the 160 Volt direct current power input into three-phase alternating current to drive the joint motors as commanded by an analog input control signal. A new set of four amplifiers were ordered to replace the damaged amplifiers, and as spares in case of another incident. When those amplifiers were installed on MABEL, they would oscillate at zero commanded input and "toggle" from position to position instead of rotating smoothly. The amplifiers were returned to the supplier and another set was ordered. The second set of replacement amplifiers exhibited the same behavior as the first set. Correspondence with engineers from the amplifier manufacturer indicated that all of the amplifiers returned operated within their specification. Additional communication about our particular application led to the manufacturer delivering a set of amplifiers that performed in a similar manner as the commissioning set. Since the amplifiers are manufactured in small quantities when ordered, a theory is that the manufacturer either received or specified a part or parts internal to the amplifier that somehow differed from the components in the initial set of amplifiers. The amplifier with new components could meet their specification during their verification tests. Unfortunately, it fundamentally effected the operation of the amplifier in our particular implementation.

C. *Communication Issues*

As mentioned previously and shown in Figure 4, MABEL is restricted to movement in a circle around a center boom on which the QNX chassis resides. The control system interface computer is located at a safe distance outside the constrained operational area of the robot. Consequently, a slip ring is necessary to connect any components required to be outside the operational area if they cannot be mounted on the central vertical boom that tethers MABEL to the operational circle. These components include the control system interface computers and the high voltage DC power supply that delivers power to the Elmo DC to three-phase AC amplifiers on-board MABEL that drive the motors that actuate each joint.

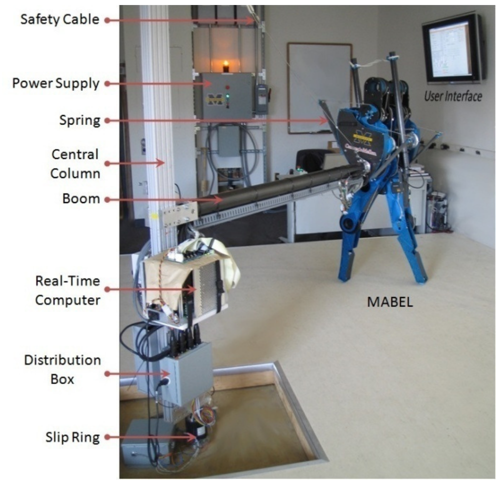


Figure 4: Overall Test Platform Setup

After the initial installation of all the necessary connections shown in Figure 5, two communications issues arose. Communication issue one occurred when there proved to be no communication between the control system interface computer and the QNX real-time control system chassis computer. After using an ohmmeter to assure that there was continuity between the two computers via an Ethernet connection, it was noted that the wires that enter and exit the slip ring and are converted to the 8-pin RJ-45 connector via gender changers were not twisted pairs. Experience with vehicle CAN bus systems (which run at a fraction of the speed of an Ethernet bus) and their behavior when even short runs of bus are *not* twisted, led to the conclusion that converting the wires into and out of the slip ring into twisted pairs was necessary. Unshielded twisted pair connections were created by inserting each pair of wires into the end of a battery powered drill and assuring a twist of at least 65 turns per meter. The wires were reconnected and the computer communication problem was solved.

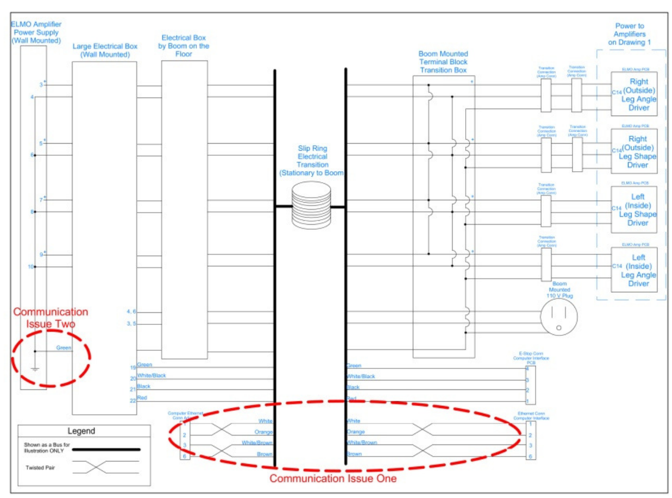


Figure 5: Communications and Power Transfer Block Diagram.

As mentioned in the Hardware section, the control command for each motor is an analog output from the QNX chassis to the Elmo amplifiers on board each leg. Communication issue two occurred when attempts at simple position-to-position control of each joint revealed that each motor would oscillate unintentionally given a steady state output position request from the control system. The oscillations were so large that steady state positioning or control would have been impossible. The oscillations occurred only when three or more motors were electrically connected to the system. Ground loop or ground versus signal interference was universally suggested as the potential issue, which turned out to be the case. After numerous attempts at isolation of system power and signal lines to assure that there was no interference due to inductive coupling, the problem persisted. After a review of the team generated system schematics and external documentation for the motor amplifiers and power supply, it was noted in the external documentation that the high power DC power supply for the motor amplifiers required that the negative leg of the high power DC supply be connected to the same earth ground as the AC supply which powers the DC supply itself (see Figure 5). Once that connection was specified and made by the licensed electricians internal to the electrical panel that delivers the 220V AC to the high voltage DC power supply, the oscillation problem disappeared.

D. Cable Stretching Issue

Steel cables connect the pulleys in the cable differentials that make up each of MABEL's joints. It has been observed in walking experiments [8] that the cables used in the differentials stretch a noticeable amount under the application of heavy loads. Experimental hopping data from [9] is used to illustrate cable stretch in one of MABEL's actuated degrees of freedom. Figure 6 shows the difference between rotations of starting pulley ($\theta_1$in Figure 7.) and rotations of end pulley ($\theta_2$in Figure 7.). Significant stretch, which reaches about 7 degrees in magnitude at the joint level, can be observed.

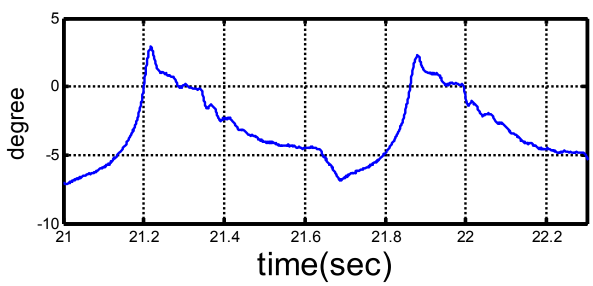


Figure 6: Cable Stretch in MABEL's Transmission Mechanism. The difference between rotations of starting pulley and end pulley of transmission, scaled to joint angle is shown.

This cable stretch can be considered as another source of compliance, and must be taken into account in the dynamic model of MABEL. Simple spring models with viscous damping are used to predict the cable stretching, and are incorporated into the dynamic model of MABEL. The simple spring model shown in Figure 7 can be modeled as,

$$\begin{aligned} \tau &= K_C x + Kd_C \dot{x} \\ x &= \theta_1 - \theta_2 \end{aligned}. \tag{1}$$

where τ is torque from the cable stretch, θ_1 is rotation angle of the starting pulley, θ_2 is rotation angle of the end pulley, K_c is a spring coefficients, and Kd_c is a damping coefficients as can be seen in Figure 7. To obtain the spring and damping coefficients of K_c and Kd_c, dynamic experiments were conducted. The obtained cable stretch model was embedded into the dynamic model of MABEL, and successfully verified by validation experiments [9].

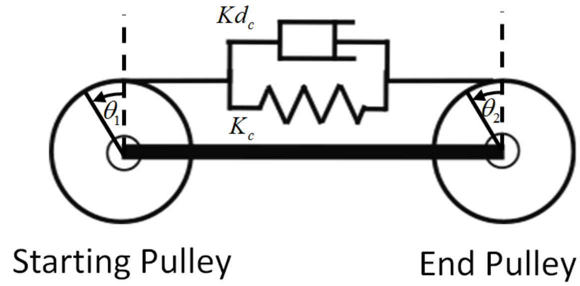


Figure 7: Cable Stretch Model

E. Sensing Resolution Issue

A walking controller is implemented on MABEL using the method of virtual constraints [10]. This requires a variable that is monotonic throughout the stance for use in parameterizing the virtual constraints. For this purpose, the absolute angle of the leg at the ground surface, as indicated in Figure 8, is used and is given by

$$\theta_s = \pi - q_{LA} - q_{Tor}. \tag{2}$$

The stance leg angle, q_{LA}, however, is not directly measured. Instead, an encoder on the motor that drives the leg angle through various cable differentials is used to estimate the leg angle. Due to the cable stretching as discussed in the previous section, θ_s is then a "stretchy" version of the true angle. Propagating this "stretched" value through the feedback controller causes control problems, resulting in oscillations and instability. One remedy was to resort to the measurements of the horizontal boom angle, q_B^h, and infer θ_s (and consequently the stance leg angle) using the relation,

$$\frac{\theta_s - \theta_s^+}{\Delta\theta_s} = \frac{q_B^h - q_B^{h+}}{\Delta q_B^h}, \tag{3}$$

where θ_s^+, q_B^{h+}, are the values of θ_s and the horizontal boom angle at the beginning of the step respectively, and $\Delta\theta_s, \Delta q_B^h$, are the nominal range of travel of θ_s and the horizontal boom angle respectively for the designed periodic walking gait. Since there are no cables in this path, the θ_s computed in this manner is not affected by cable stretch. It is, however, influenced by the resolution of the encoder on the horizontal boom angle, which is only 2048 pulses per revolution (ppr). Even with a gear-ratio of 7.4:1 between the encoder and the boom, this resolution was insufficient to obtain smooth velocity estimates of θ_s. This was easily solved by replacing the horizontal boom angle encoder with a higher resolution encoder capable of measuring 40000 ppr.

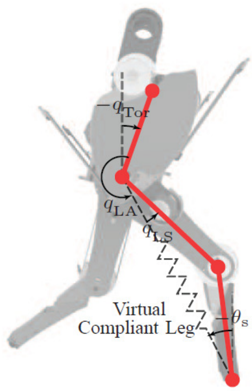


Figure 8: The virtual compliant leg created by the drivetrain through a set of differentials, and the coordinate system used for the linkage.

Using this method we can obtain good measurements of θ_s, consequently the stance leg angle and smooth velocity estimates of θ_s. However, the swing leg angle is still the "stretchy" version since the swing leg angle is still being measured by the encoder on the motor driving the link through various cable differentials. The result is imprecise swing leg angle tracking as the true angle is "stretchy", leading to pre and post-mature impacts. To solve this problem, additional encoders were introduced to measure the thigh link angle directly by using the thing link as a large gear driving an encoder. The leg angle is then constructed through a linear combination of the thigh and knee angles. As there are no longer any cables in this path, the measured values are the "true" angles. Although this gives good "true" position measurements of the leg angle, the velocity estimate using this method is very noisy due to a low resolution (2048 ppr) encoder with 1:1 measurement ratio on the knee.

For the final hybrid zero dynamics (HZD) control implementation [8], the stance and swing leg angle positions were measured from the thigh and knee encoders, while the stance leg angle velocity was estimated indirectly from the horizontal boom angle. Thus, by introducing the thigh encoder, true "non-stretched" values of the leg angles and thus θ_s were obtained, and by using the horizontal boom encoder, smooth velocity estimates of θ_s were obtained.

F. *Laser Resolution Issue*

When running experiments are carried out on MABEL, a good estimate of the robot's hip height is required to anticipate ground touch-down for transition from flight phase to stance phase. Encoders on the boom measure the horizontal and vertical angular displacements of the boom (denoted boom-X, boom-Y angles.) The boom-Y angle could be used to estimate the vertical height of the hip. From prior experiments on MABEL's predecessor, RABBIT [1], it is anticipated that the boom may flex under the heavy stress; furthermore, there could be mechanical play at the boom-robot mechanical interface. Under these circumstances, the measured boom-Y angle may no longer be sufficient to provide an accurate estimate of the hip height.

To facilitate more accurate measurements of the hip height and torso angle, and to offer a possibility of detecting obstacles, two long-range, high resolution lasers, Keyence LKG 507, were introduced. These lasers are mounted on the hip, facing the ground, but with one at the forward extremity and the other at the backward extremity of the hip mount. This enables two ground height measurements, and since the hip mount pitches with the torso, the two laser measurements could be used to measure not only the hip height, but also serve as an additional redundant (high resolution) measurement of the torso angle. With high resolution measurements of the torso angle, a smoother estimate of the velocity is also possible.

These potential uses of the lasers could not, however, be realized. Torso measurements were computed from the lasers at different resolutions. At high resolutions, the torso measurement has sudden occasional jumps, which causes large spikes in the velocity estimate. At lower resolution, the spikes disappear, but the velocity estimate is no better than that obtained from the encoders. This prevented use of the lasers as means of a reliable measurement of the torso angle. A similar problem exists with laser resolution when sensing boom height.

One possibility for the spikes is due to electronics. We used a 21-bit digital interface from the laser head units for communication which introduces the possibility of occasional bit errors while reading the large number of bits at a high data rate. Two other possible reasons for the measurement spikes are related to the high resolution and optical nature of the sensors. One, when the lasers are set near their highest resolution, the flatness, or lack thereof, of the target contributes to loss of accuracy. MABEL walks on a simple linoleum covered plywood platform, not a machined to tolerance metal bedplate, so variation in robot height and angle exist from that source. Two, since the floor does not offer an ideal reflective target for the lasers, additional noise may be incurred due to diffusion or deflection of the laser output. Project deadlines and deliverables forced continuation of work using encoders. Further investigation of the laser implementation will occur prior to and during running and obstacle handling experiments.

G. *Software Throughput Issue*

The QNX real-time DAQ system runs one complete cycle comprising of data-acquisition from the sensors, data-processing to compute a control signal, and data-output to the actuators, all in less than 1 millisecond (ms). A hardware watchdog timer is implemented that powers down the system if the computation time exceeds this hard real-time specification. To enable such a fast throughput, the controller code needs to be highly optimized. Simple controllers, such as PD controllers, have a very small computing overhead and are easily implemented along with the computation overhead of data acquisition, velocity estimation, data logging, and safety checking. With complex controllers such as the HZD controller [8] deployed on MABEL, the entire dynamic model of the robot must be computed and then inverted to calculate the feedback linearizing torque. This places a high computing demand on the processor. Early implementations of the HZD controller employed C arrays and C++ vectors for implementing basic linear algebra operations. This implementation always triggered the watchdog timer during run-time, indicating that the computations exceeded the hard real-time threshold.

Standard methods to improve performance by code profiling and optimizing bottlenecks did not improve performance significantly. The entire code was then remapped to use C++ expression templates [11] and the Boost basic linear algebra library [12], enabling delayed expression evaluation, and thereby vectorizing several operations. With this method of software thrifting, the computing time dropped below the 1ms threshold and the HZD controllers were successfully implemented in experiments.

IV. Summary

Any newly specified and designed electromechanical system with real-time control will likely require a significant effort to assure operational expectations are met during the commissioning and implementation phases. Typical troubleshooting conventions, such as, "When in doubt refer to the manual, data sheets or documentation, and always check the power supplies" certainly contributed to successful commissioning. Other more complex implementation concepts were also essential. First, the assembled technical team had the breadth of experience necessary to address problems ranging from systems theory to practical application. Second, the team understood that methods and designs beyond the boundaries of local design can have a significant effect; specifically, the manufacturing of printed circuit boards and the possibility of changes to third party replacement "black boxes" within a design. Third, that some modifications may be required during the implementation phase of even the most well thought out design for a variety of reasons: a small detail that may be missed when a design is handed off to a number of different team members, design assumptions that may prove inaccurate or impossible to achieve, and project deadlines that may drive the use of alternative methods to reach goals on time.

The successful implementation of an experimental bipedal platform named MABEL at the University of Michigan Ann Arbor required the use of common troubleshooting conventions and several more complex implementation concepts. The commissioning and implementation team identified and corrected or worked around issues with printed circuit board layout and manufacturing, a third party "black box" subsystem, system communications, identification and characterization of cable stretching, sensing system resolution, and real-time computer processing speed. Initial project goals of successful walking, fast walking at speed of just over 1.5 meter/second, hopping and walking while small perturbations to the walking gait are introduced (a small push in either the forward or backward direction, for example) have been achieved. Video documentation of various experiments is available on YouTube at www.youtube.com/DynamicLegLocomotion. Successful implementation of the entire system allows continuing research of control methods, and additional challenges in real-time bipedal locomotion control such as running, where both of MABEL's feet will leave the ground for a short flight period during each stride, and obstacle handling, where control system robustness is verified by changing the level at which a stride terminates or more simply, by adding steps to or removing steps from the path of travel.

Acknowledgments

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