

# Inverted Pendulum Control using a BeagleBone Blue

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## Introduction

The objective of this project is design and implement a complete control system for an inverted pendulum. Control will be applied to the angle of the robotic body and to the position relative to the ground. Two nested control loops will be used in order to achieve this. MatLab is used as a tool to design the concept and C is used to implement the design on the eduMIP platform provided by the UCSD Coordinated Robotics Lab.

## Inner loop design

The first task is to design an inner loop controller to stabilize the body angle denoted  $\theta$  around a given setpoint  $\theta_{ref}$ . This process begins with finding the system transfer function G1 from the motor input duty cycle  $u$  to the body angle  $\theta$ . The transfer function is given by,

$$G1 = \frac{\theta}{u} = \frac{-882.7s}{s^3 + 44.15s^2 - 192.8s - 2299} \quad (1)$$

The Bode plot of G1 is given by figure 1.

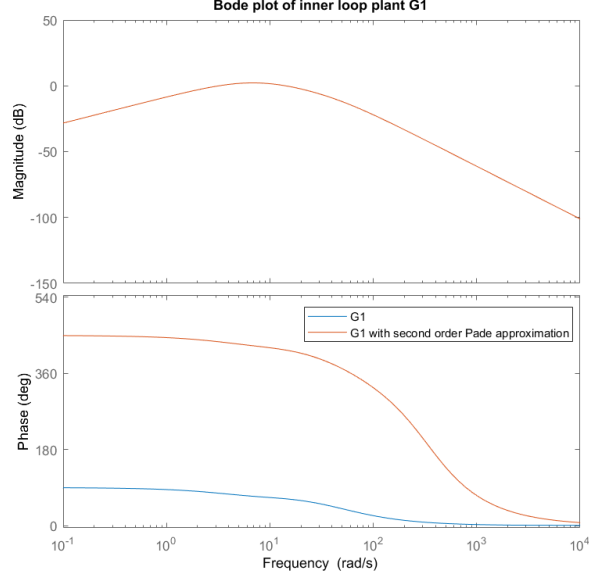


Figure 1: Bode plot of the inner loop plant with and without second order Pade approximation for delay coming from zero order hold of the discrete inner loop controller.

An analysis of the pole and zero placement of G1 reveals that it has poles located at  $-47.2061$ ,  $8.6696$ ,  $-5.6165$  and one zero at the origin. To get this system stable, a lag compensator that cancels the zero at the origin is necessary to bring the right hand pole to the left half plane. Cancelling a zero at the origin can be tricky business, but since it is known at this stage, that an outer loop will be implemented, we can assure that stability is kept, even though we might miss by a small amount when cancelling. The lag controller  $D1_{lag}$  is of the form

$$D1_{lag} = \frac{s + 5.6165}{s}, \quad (2)$$

where a cancellation of the left half plane pole of the plant G1 is a safe cancellation since it contributes in the event of a missed cancellation to an exponentially decaying term in the expression of the output in the time domain. When the controller  $D1_{lag}$  is tuned with some proportional gain, stability can be achieved, but the system is not robust enough as can be seen by the low phase margin and oscillatory behavior of figure 2.

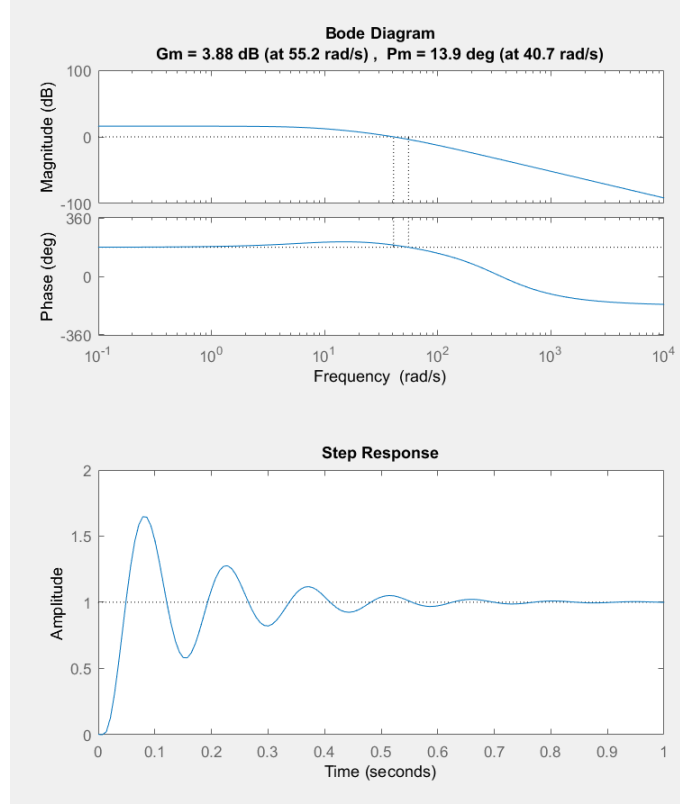


Figure 2: Bode plot of the open loop system  $D1_{lag}G1$  tuned with some proportional gain to achieve stability.

To get a more stable system, a lead compensator  $D1_{lead}$  is added. The lead compensator will be centered to have its maximum phase gain at the desired cross-over frequency  $\omega_{c1}$  of the open loop system  $L1 = D1G1$  to increase robustness. A good starting point for the the cross-over frequency  $\omega_{c1}$  is to set it to a tenth of the Nyquist frequency where the Nyquist frequency is half of the sampling frequency of the IMU, which is 100 Hz. This yields a cross-over frequency

$$\omega_{c1} = 10\pi \text{ rad/sec.} \quad (3)$$

One can also evaluate the chosen cross-over frequency according to the tuning guideline ( $\omega_n = 1.8/t_r$ ) that specifies the cross-over frequency when the rise time to a step input is given. A rise time of around 0.05 seconds yields the specified cross-over frequency. This should reflect the natural time period of the pendulum when it is not inverted, but a simply experiment shows that the real world period time is closer to 0.5 seconds. This means that the inputs  $u$  will likely vary around this critical frequency during operation and it is thus important that stability is preserved for these frequencies. Using a cross-over

frequency higher than the natural frequency means that we are on the safe side of operation since the closed loop system will not reject the important inputs frequencies.

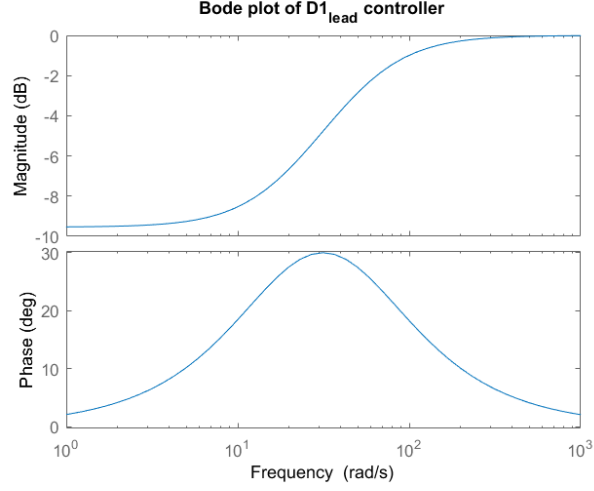


Figure 3: Bode plot of the controller  $D1_{lead}$  centered at  $\omega_{c1}$ .

$$D1_{lead} = \frac{s + 18.14}{s + 54.41} \quad (4)$$

with a Bode plot given by figure 3. Using  $D1_{lead}$  together with  $D1_{lag}$  in a cascade formation together with an appropriate gain constant yields the complete inner loop controller determined by

$$D1 = K_{D1} D1_{lead} D1_{lag} = \frac{-2.94s^2 - 69.84s - 299.5}{s^2 + 54.41} \quad (5)$$

The root locus of the system displaying the placement of the closed loop system poles is plotted together with the step response of the closed loop system, open loop  $L1$  Bode plot and inner loop controllers in figure 4

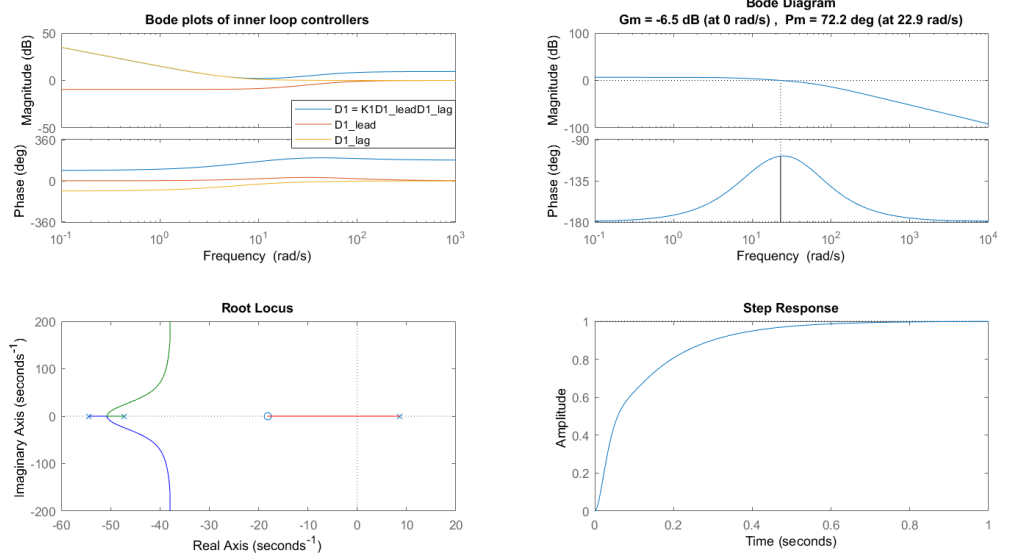


Figure 4: The root locus of the system displaying the placement of the closed loop system poles is plotted together with the step response of the closed loop system, open loop  $L1$  Bode plot and inner loop controllers.

The discrete equivalent controller to  $D1(s)$  is found by transforming the controller with Tustin's approximation with prewarping around the crossover frequency. The result is

$$D1(z) = \frac{u}{\theta_e} = \frac{-2.589z^2 + 4.602z - 2.037}{z^2 - 1.569z + 0.5695}, \quad (6)$$

where  $\theta_e = \theta_{ref} - \theta$ , the body angle error and  $u$  is the duty cycle which is the input to the PWM signal going to the motors.

As a final check of the inner loop controller, a second order Pade approximation of a delay can be applied to the plant  $G1$ . This is tested due to the fact that there will inherently be a delay of the form  $e^{-ds}$  from the DAC (Digital to Analog Converter) when the discrete controller delivers its output to the continuous plant  $G1$ . The sampling period time of the IMU is  $h = 0.01$  s and the delay from the ZOH is  $d = h/2$ . The plant using a second order approximation is given by figure 1 and a corresponding analysis as given in figure 4 can be found in figure 5. As can be seen, the phase margin has dropped by around 7 degrees and is therefore still far from instability.

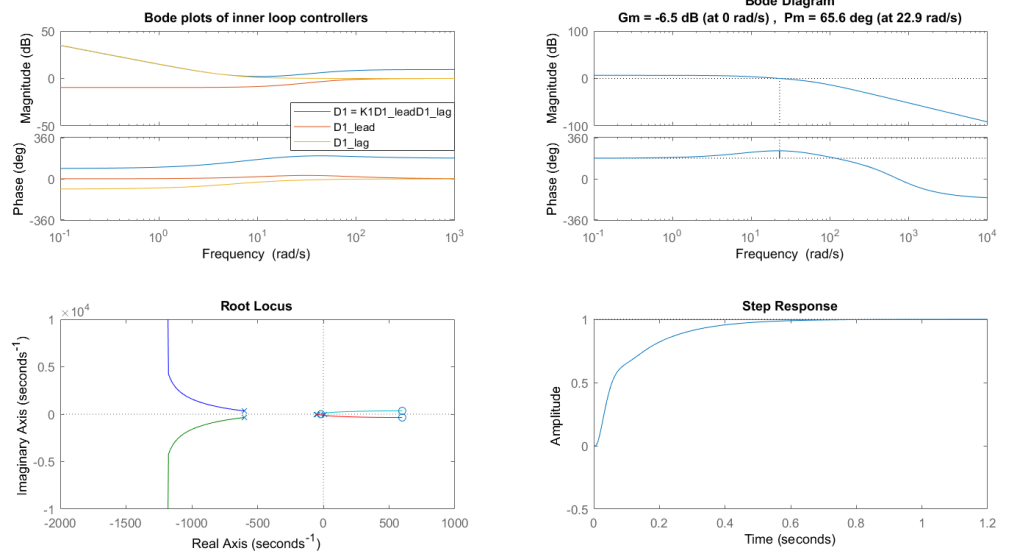


Figure 5: Bode plot of the controller  $D1_{lead}$  centered at  $\omega_{c1}$ .

## Outer loop design

First assuming that the outer loop has much slower dynamics compared to the inner loop, the outer loop can be designed on the assumption that the closed inner loop will be very close to unity for all frequencies of interest for the outer loop. Therefore, a crossover frequency ten times smaller than the crossover frequency of the inner loop is used and the design of the outer loop controller is first made with the inner closed loop assumed to be one. From Newtons equations of motion the relationship between the body angle  $\theta$  and the position  $\phi$  can be calculated in the Laplace domain given by a transfer function

$$G2 = \frac{\phi}{\theta} = \frac{-1.476s^2 + 2.622 \times 10^{-15} + 128.9}{s^2}. \quad (7)$$

The Bode plot of the outer loop system is given by figure 6.

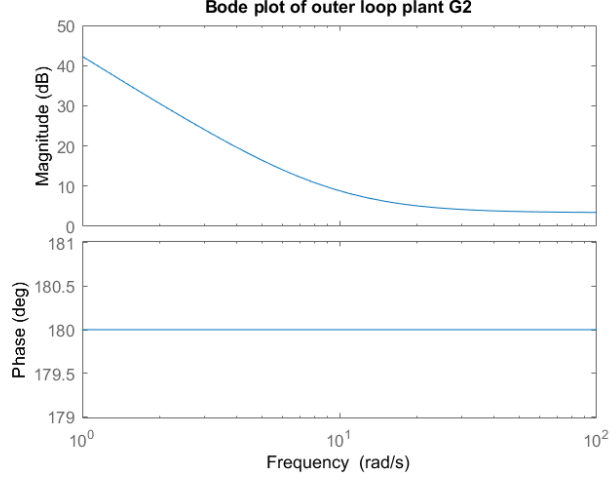


Figure 6: Bode plot of the outer loop plant G2.

Looking at the phase response which is -180 degrees over all frequencies, it is obvious that a lead compensator is needed. Designing a lead compensator  $D2_{lead}$  centered at  $\omega_{c2} = \omega_{c1}/10$  yields

$$D2_{lead} = \frac{s + 0.5736}{s + 17.21} \quad (8)$$

A lag compensator  $D2_{lag}$  was also added to bump up the gain at lower frequencies. The robot works absolutely fine without this compensation, but the robot behaves more smoothly with it than without.

$$D2_{lag} = \frac{s + 0.06283}{s + 0.01571} \quad (9)$$

With an appropriate gain factor the complete outer loop controller then becomes

$$D2 = K2D2_{lead}D2_{lag} = \frac{0.1738s^2 + 0.1106s + 0.006263}{s^2 + 17.22s + 0.2703} \quad (10)$$

The corresponding plot to figure 4 but for the outer loop is given by 7

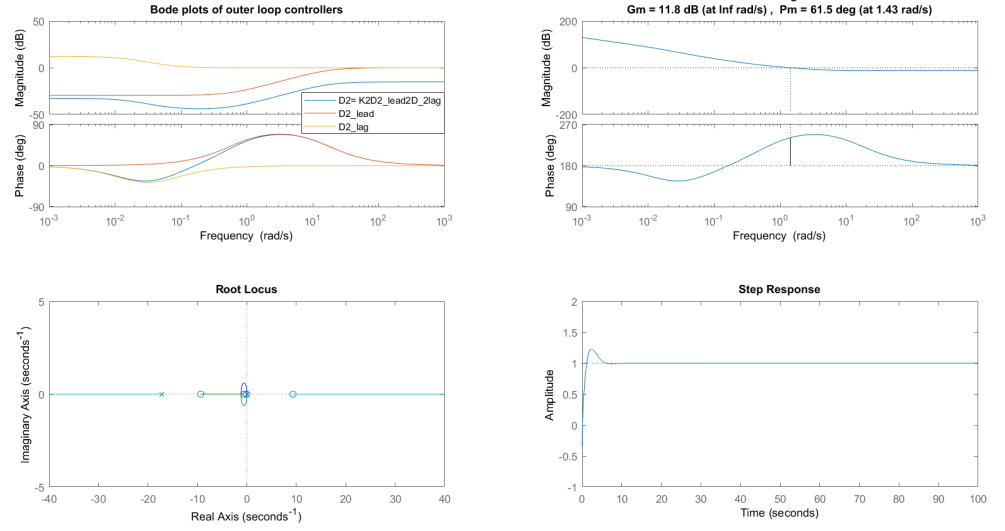


Figure 7: Bode plot of outer loop controllers, Bode plot of open loop  $L2 = D2G2$  system, root locus and step response of the closed loop system of  $L2$ .

Adding a Pade approximated delay of  $e^{-ds}$  of fourth order with  $d = h/2$  with  $h = 0.05$  s yields the following result given by figure 8



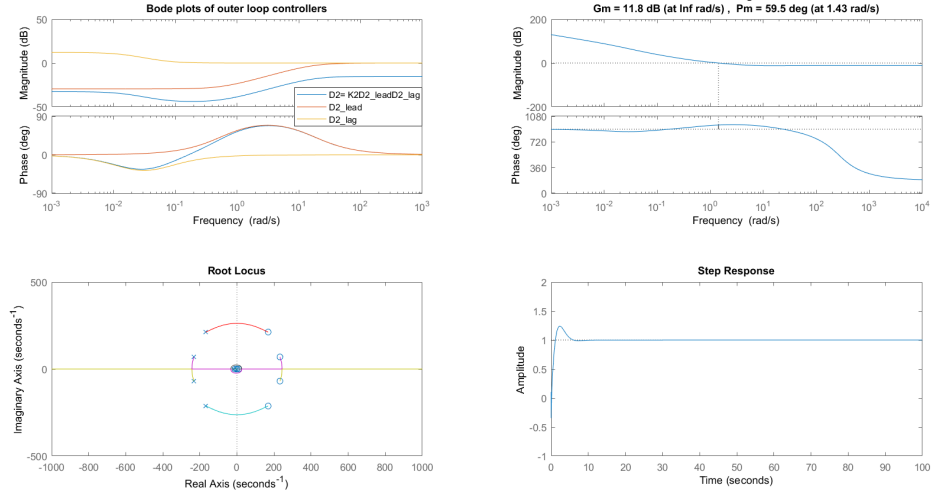


Figure 8: Bode plot of outer loop controllers, Bode plot of open loop  $L2 = D2G2$  system, root locus and step response of the closed loop system of  $L2$ . The only difference to figure 7 is the addition of a the delay approximation to  $G2$ .

The delay occurs due to the zero order hold of the DAC in  $D2$ . A phase loss of only 2 degrees can be seen in figure 8 and thus the system is stable.

The final step is to include the closed loop transfer function  $T1 = \frac{L1}{1+L1}$ , where  $L1 = D1G1$  to the outer loop system. The results, using a second order Pade approximation in  $G1$  and a fourth order Pade approximation in  $G2$  yields the final result as seen in figure 9

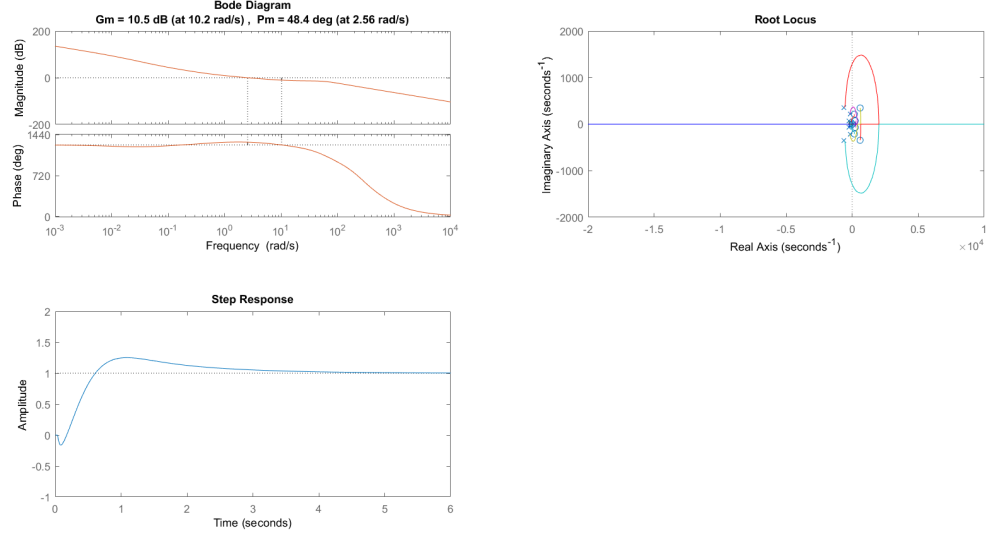


Figure 9: System analysis with the characteristics of the inner loop included. Root locus, step response and Bode plot all show stable behaviors.

Note the nonminimum phase behavior as can be seen in the step response of figure 9. This is expected and is a natural behavior of a MiP.

Finally the discrete version of D2 is found by utilizing Tustin's approximation around the crossover frequency  $\omega_{c2}$  and the result is

$$D2(z) = \frac{0.1233z^2 - 0.2428z + 0.1195}{z^2 - 0.397 + 0.3972} \quad (11)$$

## Code

```

1
2 /*
   *****
3 * FINAL_PROJECT.c
4 *
5 * This program retrieves the angle estimates from the IMU and
   passes the values
6 * through a complementary filter to for a more accurate description
   of the angle
7 * and then uses a body angle reference set point to balance around.
   Two controllers
8 * are arranged in a successive loop closure to make the robot stay
   in the same

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9  * position. The sampling rate of the IMU is 100 Hz and the inner
    loop runs at 100 Hz
10 * while the outer loop runs at 20 Hz. The program prints to the
    screen at
11 * 10 Hz.
12 *****/
13
14 // usefulincludes is a collection of common system includes
15 #include <rc.usefulincludes.h>
16 // main roboticscape API header
17 #include <roboticscape.h>
18
19 //Define inner and outer loop timesteps
20 #define INNER_TIMESTEP 0.01
21 #define OUTER_TIMESTEP 0.05
22
23 //Define D1 gain tuning factor, overload and reset factor
24 #define D1_GAIN 1.02 //Tuned for good performance
25 #define D1_OVERLOAD_TIMEOUT 50
26 #define D1_RESET_TIMEOUT 200
27
28 //Define D2 gain tuning factor
29 #define D2_GAIN 1.0 //No tuning needed
30
31 #define STEERING_GAIN 0.25
32 #define ANGLE_OFFSET 0.31
33 #define START_ANGLE_RANGE 0.2
34 #define MAX_LEAN 1.2
35
36 //Motor and encoder controls
37 #define LMOTOR_POLARITY 1
38 #define RMOTOR_POLARITY -1
39
40 #define RMOTOR_CHANNEL 2
41 #define LMOTOR_CHANNEL 3
42
43 #define RENCODER_CHANNEL 2
44 #define LENCODER_CHANNEL 3
45 #define LENCODER_POLARITY 1
46 #define RENCODER_POLARITY -1
47
48 #define GEARBOX 4*15*35.555
49
50
51 //Function declarations
52 void on_pause_pressed();
53 void on_pause_released();
54 void* print_thread_func();
55 void* outer_loop_thread_func();
56 void inner_loop();
57 void reset_controller();
58
59
60 //Define an armstate enum, used to turn various loops and checks on
    /off.
61 typedef enum arm_state_t{

```

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62         DISARMED,
63         ARMED
64     } arm_state_t;
65
66     arm_state_t armstate=DISARMED;
67     //Initialize inner loop body angle variables.
68     double theta_a_raw = 0;
69     double theta_g_raw = 0;
70     double theta_g_raw_last = 0;
71     double theta_a = 0;
72     double theta_f = 0;
73     double theta_g = 0;
74
75     //Initialize body angle error variables
76     double theta_e = 0;
77     double theta_e_last = 0;
78     double theta_e_last_last = 0;
79
80     //Initialize body angle reference
81     double theta_ref = 0;
82     double theta_ref_last = 0;
83     double theta_ref_last_last = 0;
84
85     //Initialize inner loop overload and reset timer
86     int inner_overload_timer = 0;
87     int inner_reset_timer = 0;
88     //Initialize duty cycle variables
89     double u = 0;
90     double u_last = 0;
91     double u_last_last = 0;
92
93     //Initialize outer loop setpoint variable
94     double phi_ref = 0;
95     double phi = 0;
96     double phi_R = 0;
97     double phi_L = 0;
98     double phi_diff = 0;
99     double steeringinput = 0;
100
101     //Initialize outer loop setpoint errors
102     double phi_e = 0;
103     double phi_e_last = 0;
104     double phi_e_last_last = 0;
105
106
107     //Struct to hold imu data
108     rc_imu_data_t imudata;
109
110     /*
111
112
113     * int main()
114     *
115     * This template main function contains these critical components
116     * - call to rc_initialize() at the beginning
117     * - initialize IMU and threads
118     * - main while loop that checks for EXITING condition
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```

117 * - rc_cleanup() at the end
118 ****
119 */
120 int main(){
121     //Always initialize cape library first
122     if(rc_initialize()){
123         fprintf(stderr,"ERROR: failed to initialize
124         rc_initialize(), are you root?\n");
125         return -1;
126     }
127     //Connect buttons to functions
128     rc_set_pause_pressed_func(&on_pause_pressed);
129     rc_set_pause_released_func(&on_pause_released);
130     //Configure the IMU
131     rc_imu_config_t conf = rc_default_imu_config();
132     //Set up the imu for interrupt operation
133     if(rc_initialize_imu_dmp(&imudata, conf)){ //Points at the
134         data struct where we store the imu-values and to the
135         configurations of the imu stored in conf
136         fprintf(stderr,"rc_initialize_imu_failed\n");
137         return -1;
138     }
139     if(rc_read_accel_data(&imudata)<0){
140         printf("read accel data failed\n");
141     }
142     printf("| Angle | Motor input | Position |\n");
143     theta_a = atan2(-imudata.accel[2],imudata.accel[1]); //Set
144     the output of low pass filter to the current accelerometer
145     value to account for steady state
146     //Create thread for printing angle estimates
147     pthread_t print_thread;
148     pthread_create(&print_thread, NULL, print_thread_func, (
149     void*) NULL);
150     //Set priority of thread
151     struct sched_param params_print_thread;
152     params_print_thread.sched_priority = 1;
153     pthread_setschedparam(print_thread, SCHED_FIFO,&
154     params_print_thread);
155     //Make thread for outer loop (setpoint control)
156     pthread_t outer_loop_thread;
157     pthread_create(&outer_loop_thread, NULL,
158     outer_loop_thread_func, (void*) NULL);
159     //Set priority of thread
160     struct sched_param params_outer_loop_thread;
161     params_outer_loop_thread.sched_priority = 10;
162     pthread_setschedparam(outer_loop_thread, SCHED_FIFO,&
163     params_outer_loop_thread);
164     //Give the IMU an interrupt function

```

```

164     rc_set_imu_interrupt_func(&inner_loop);
165
166     rc_set_state(RUNNING);
167
168
169     // Keep looping until state changes to EXITING
170     while(rc_get_state() != EXITING){
171         if(armstate==ARMED) {
172             rc_set_led(GREEN,ON);
173             rc_set_led(RED,OFF);
174         }
175
176         else if(armstate==DISARMED) {
177             rc_set_led(GREEN,OFF);
178             rc_set_led(RED,ON);
179         }
180         rc_usleep(1000000);
181     }
182
183     //Exit cleanly
184     printf("Waiting for print thread to join \n");
185     pthread_join(print_thread, NULL);
186     printf("Print thread joined \n");
187     printf("Waiting for setpoint thread to join \n");
188     pthread_join(outer_loop_thread, NULL);
189     printf("Outer loop thread joined \n");
190
191     rc_power_off_imu();
192     rc_cleanup();
193     return 0;
194 }
195
196 //The interrupt function is called everytime the IMU has new data
197 //available (100 Hz) and filters the data that is collected by
198 //the imu
199 void inner_loop() {
200     //Complementary filter cross-over frequency as a static
201     //variable which means that it is only instantiated once.
202     static double wcfiler = 0.5;
203
204     theta_a_raw = atan2(-imudata.accel[2],imudata.accel[1]);
205     theta_g_raw_last = theta_g_raw;
206     theta_g_raw = theta_g_raw + imudata.gyro[0]*PI/180*
207     INNER_TIMESTEP;
208
209     theta_a = -(wcfiler*INNER_TIMESTEP-1)*theta_a + wcfiler*
210     INNER_TIMESTEP*theta_a_raw;
211
212     theta_g = -(wcfiler*INNER_TIMESTEP-1)*theta_g +
213     theta_g_raw - theta_g_raw_last;
214
215     theta_f = theta_a + theta_g+ANGLE_OFFSET;
216
217     // INNER LOOP CONTROLLER
218     theta_e_last_last = theta_e_last;
219     theta_e_last= theta_e;
220     theta_e = theta_ref-theta_f;

```

```

215
216 //Evaluate inner loop difference equation
217 u_last_last = u_last;
218 u_last = u;
219 u = D1_GAIN*(1.569*u_last-0.5695*u_last_last-2.589*theta_e
+4.602*theta_e_last-2.037*theta_e_last_last);
220
221 //Prevent windup by setting max and min values for the
motor input
222 if(u>=1){
223     u=1;
224 }
225 if(u<=-1){
226     u=-1;
227 }
228
229 /*****
230 Perform checks on status of system, and react accordingly
231 *****/
232
233 //Turn off motor if exiting
234 if(rc_get_state()==EXITING){
235     rc_disable_motors();
236     return;
237 }
238
239 /*initiate a reset timer that checks if the robot is lying
down, ready to be picked up to balance.
240 This is used to prevent the motors from running when the
robot is picked up */
241 if(theta_f > -1.7 && theta_f < -1.5){
242     inner_reset_timer++;
243 }
244
245 if(fabs(theta_f) < START_ANGLE_RANGE && armstate ==
DISARMED) {
246     if(inner_reset_timer > D1_RESET_TIMEOUT){
247         reset_controller();
248         rc_enable_motors();
249         armstate = ARMED;
250         inner_reset_timer = 0;
251     }
252 }
253
254 //If the robot is disarmed, do nothing
255 if(armstate == DISARMED) {
256     return;
257 }
258
259
260 //If robot has tipped past point of no return, stop trying
261 if(fabs(theta_f)>MAX_LEAN){
262     printf("\r I have fallen over. Need help! \n");
263     reset_controller();
264     rc_disable_motors();
265     armstate = DISARMED;
266 }

```

```

267
268 //Initiate check if the robot has gone stuck, to prevent
motors from breaking
269 if(fabs(u)>0.95){
270     inner_overload_timer++;
271 }
272 else{
273     inner_overload_timer=0;
274 }
275 if(inner_overload_timer > D1.OVERLOAD_TIMEOUT){
276     printf("\r I have gone stuck. Rescue me! \n");
277     reset_controller();
278     rc_disable_motors();
279     armstate = DISARMED;
280     inner_overload_timer = 0;
281     return;
282 }
283
284
285 //Proportional steering controller to keep robot pointing
in approximately the right direction
286 steerinput=STEERING_GAIN*phi_diff;
287
288 rc_set_motor(LMOTOR_CHANNEL, LMOTOR.POLARITY*(u-
steerinput));
289 rc_set_motor(RMOTOR_CHANNEL, RMOTOR.POLARITY*(u+
steerinput));
290
291 return;
292 }
293
294 void* print_thread_func(){
295 while(rc_get_state() != EXITING) {
296     printf("\r");
297     printf("|%6.3f |%6.3f |%6.3f |", theta_f, u, phi);
298     fflush(stdout);
299     rc_usleep(100000);
300 }
301 return NULL;
302 }
303
304 void* outer_loop_thread_func(){
305 while(rc_get_state() != EXITING){
306     phi_R = (RENCODER.POLARITY*rc_get_encoder_pos(
RMOTOR.CHANNEL)*2*PI)/(GEARBOX);
307     phi_L = (LENCODER.POLARITY*rc_get_encoder_pos(
LMOTOR.CHANNEL)*2*PI)/(GEARBOX);
308
309 //Take average of left and right encoder and add body angle
310 phi = (phi_R+phi_L)/2 +theta_f;
311
312 //Difference between wheel positions for use in steering
controller
313 phi_diff = phi_L-phi_R;
314
315 phi_e_last_last = phi_e_last;
316 phi_e_last = phi_e;

```



```

317     phi_e = phi_ref - phi;
318
319     theta_ref_last_last = theta_ref_last;
320     theta_ref_last = theta_ref;
321
322     //Outer loop difference equation
323     theta_ref = D2.GAIN*(1.397*theta_ref_last - 0.3972*
theta_ref_last_last + 0.1233*phi_e - 0.2428*phi_e_last +
0.1195*phi_e_last_last);
324     rc_usleep(OUTER_TIMESTEP*1000000);
325     }
326     return NULL;
327 }
328
329 /*
*****

330 * void on_pause_pressed()
331 *
332 * If the user holds the pause button for 2 seconds, set state to
    exiting which
333 * triggers the rest of the program to exit cleanly.
334 *****
    */
335 void on_pause_pressed(){
336     int i=0;
337     const int samples = 100;          // check for release 100
    times in this period
338     const int us_wait = 2000000; // 2 seconds
339
340     // now keep checking to see if the button is still held
    down
341     for(i=0;i<samples;i++){
342         rc_usleep(us_wait/samples);
343         if(rc_get_pause_button() == RELEASED) return;
344     }
345     printf("long press detected, shutting down\n");
346     rc_set_state(EXITING);
347     return;
348 }
349
350 void on_pause_released(){
351     // toggle between armed and disarmed modes
352     if (armstate==ARMED){
353         reset_controller();
354         rc_disable_motors();
355         armstate = DISARMED;
356     }
357     else if (armstate==DISARMED){
358         if(fabs(theta_f) < START_ANGLE_RANGE) {
359             reset_controller();
360             rc_enable_motors();
361             armstate = ARMED;
362         }
363     }
364     return;
365 }

```

```

366
367 void reset_controller(){
368     //Reset encoders and all variables to reset controller
369     rc_set_encoder_pos(RMOTOR.CHANNEL,0);
370     rc_set_encoder_pos(LMOTOR.CHANNEL,0);
371
372     phi_e = 0;
373     phi_e_last = 0;
374     phi_e_last_last = 0;
375
376     theta_ref = 0;
377     theta_ref_last = 0;
378     theta_ref_last_last = 0;
379
380     u = 0;
381     u_last = 0;
382     u_last_last = 0;
383
384     theta_e = 0;
385     theta_e_last = 0;
386     theta_e_last_last = 0;
387 }

```