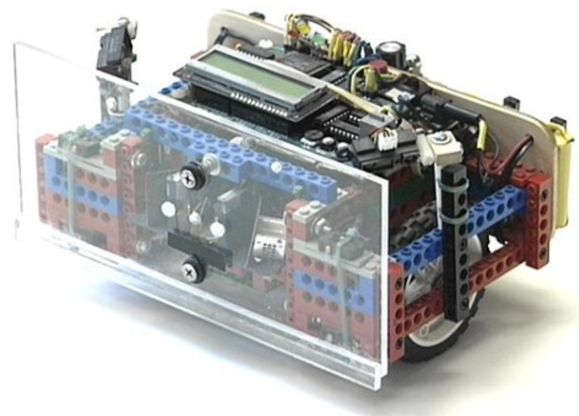
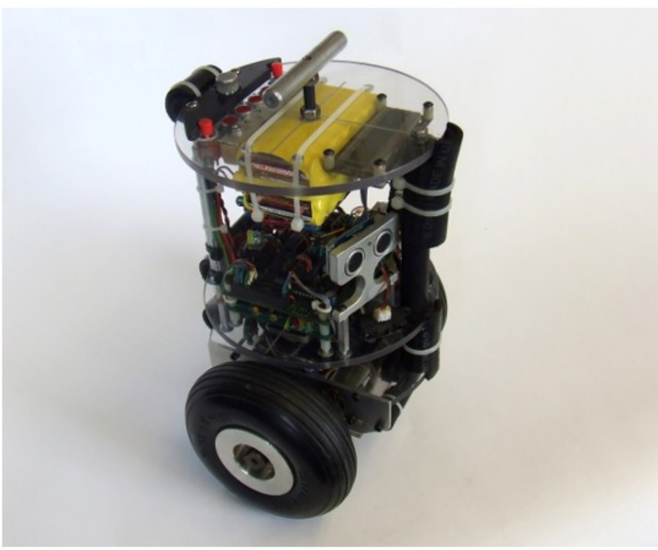
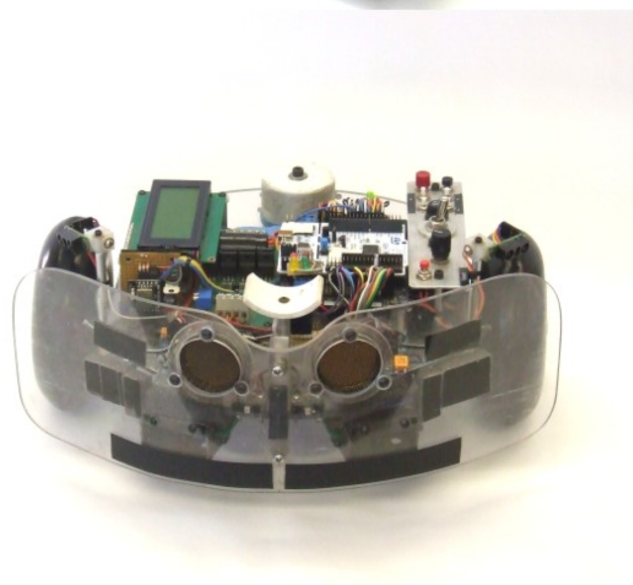
Robot Navigation

DPRG June 2021
David P. Anderson







Update: 19 Aug 2021
V1.1

Emergent Navigation:

Emergent: Complex high level behavior arising from the interaction of multiple simple low level behaviors

"How Waypoint Navigation is Implemented on my Robots"

I. Motion Control

II. Waypoint Navigation

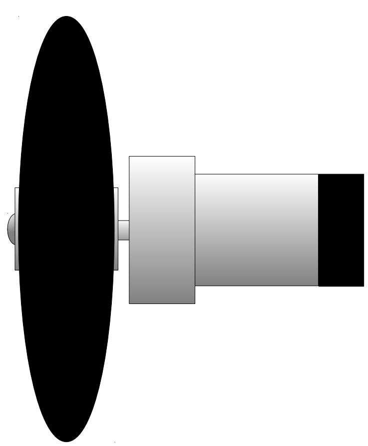
III. Advanced Navigation Modes

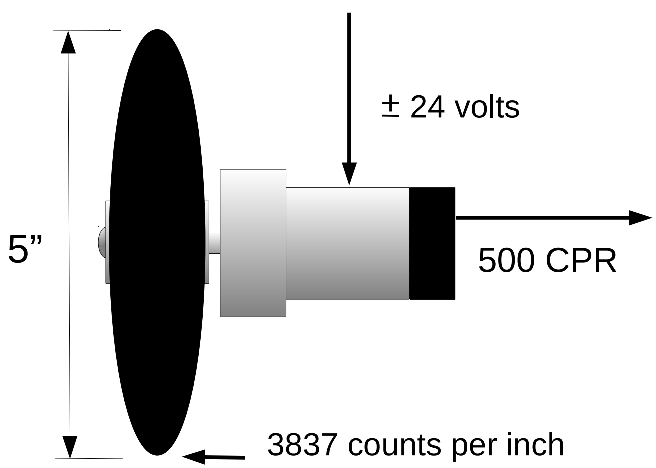
I. Motion Control

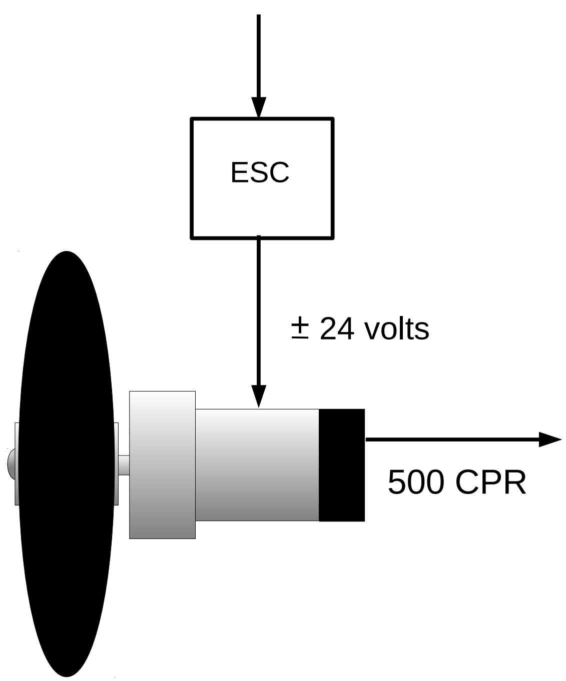
A. Motor Control

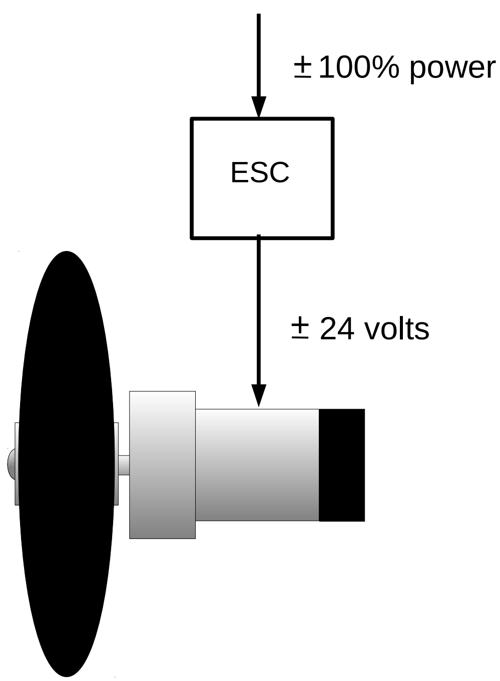
B. Arbiter Control Loop

C. Example Behaviors

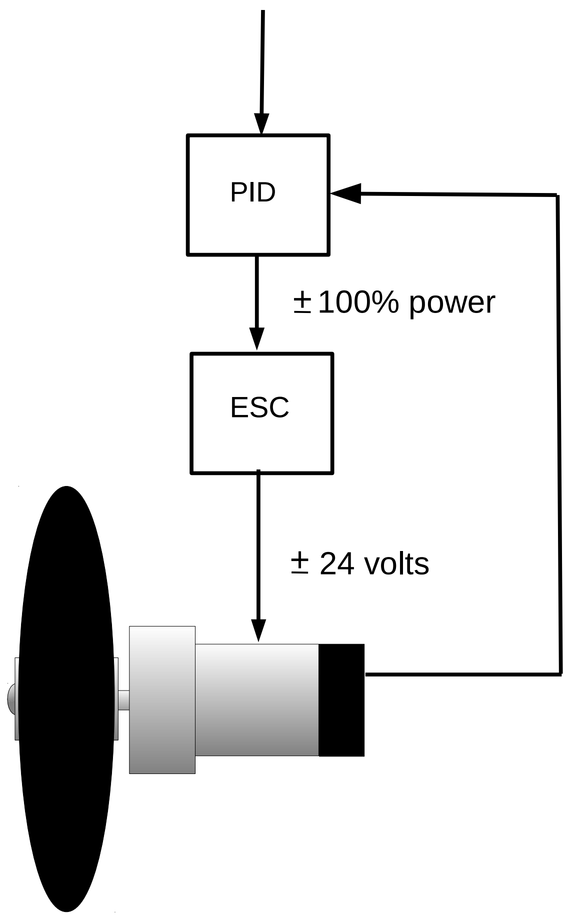



± 24 volts
5”
500 CPR
3837 counts per inch

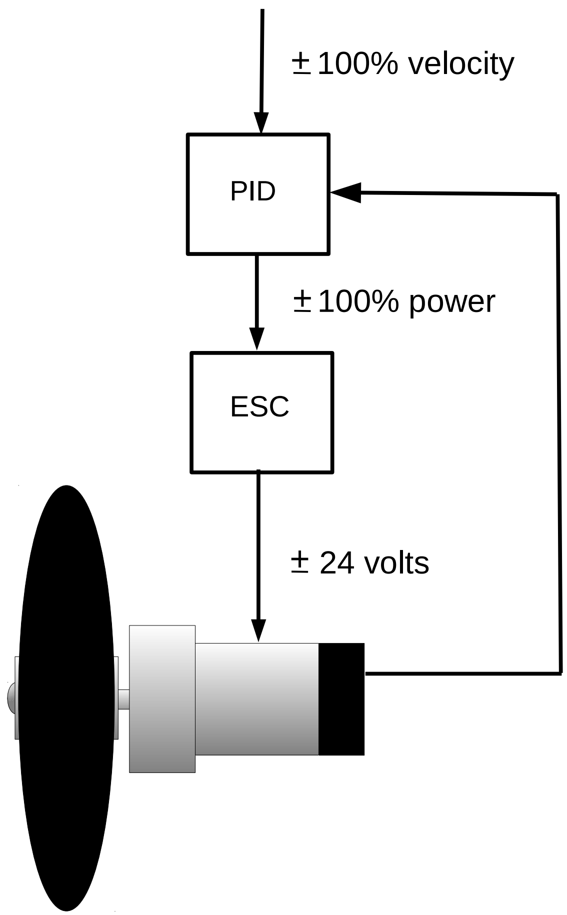

ESC
± 24 volts
500 CPR



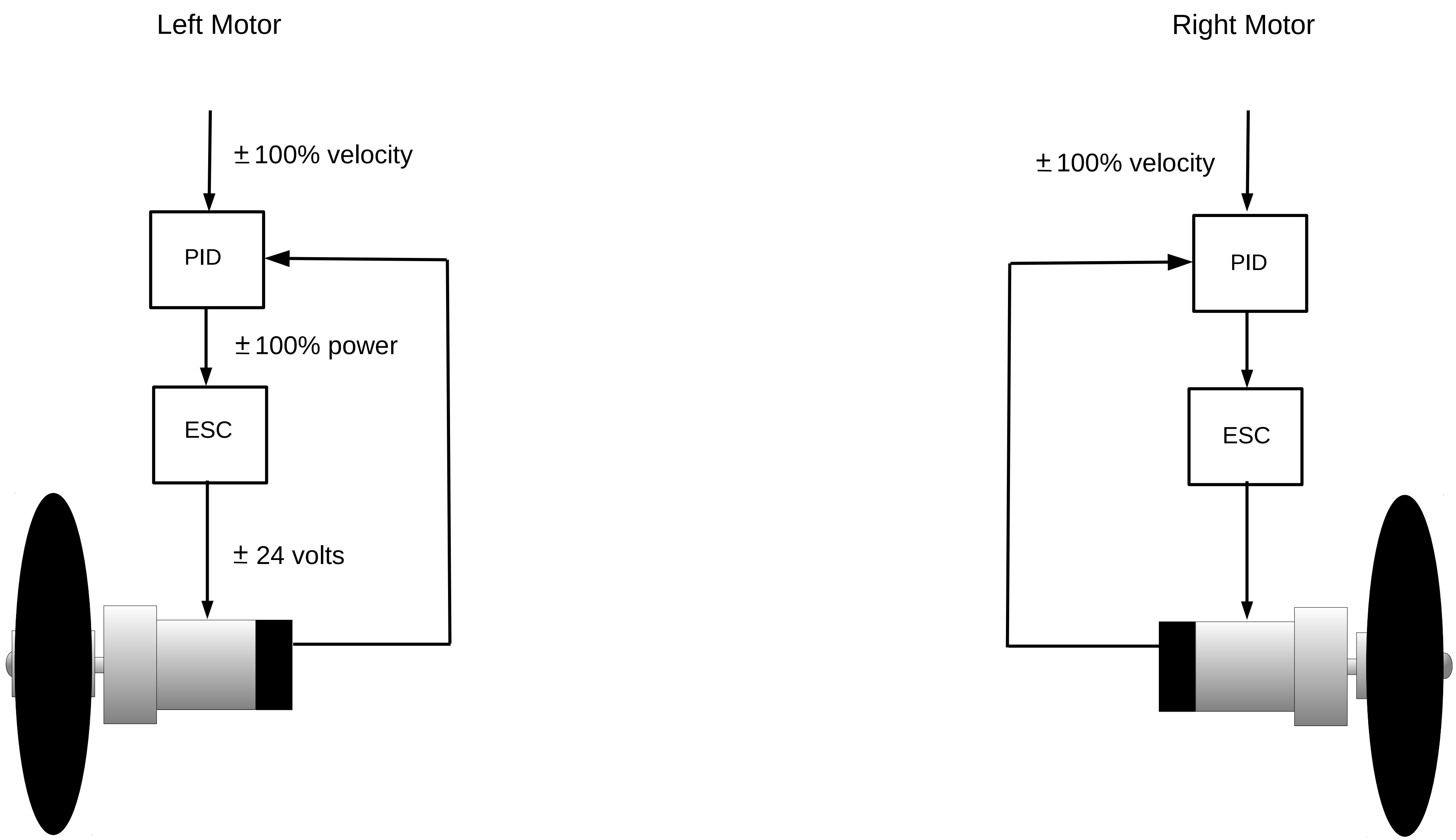
Open loop control



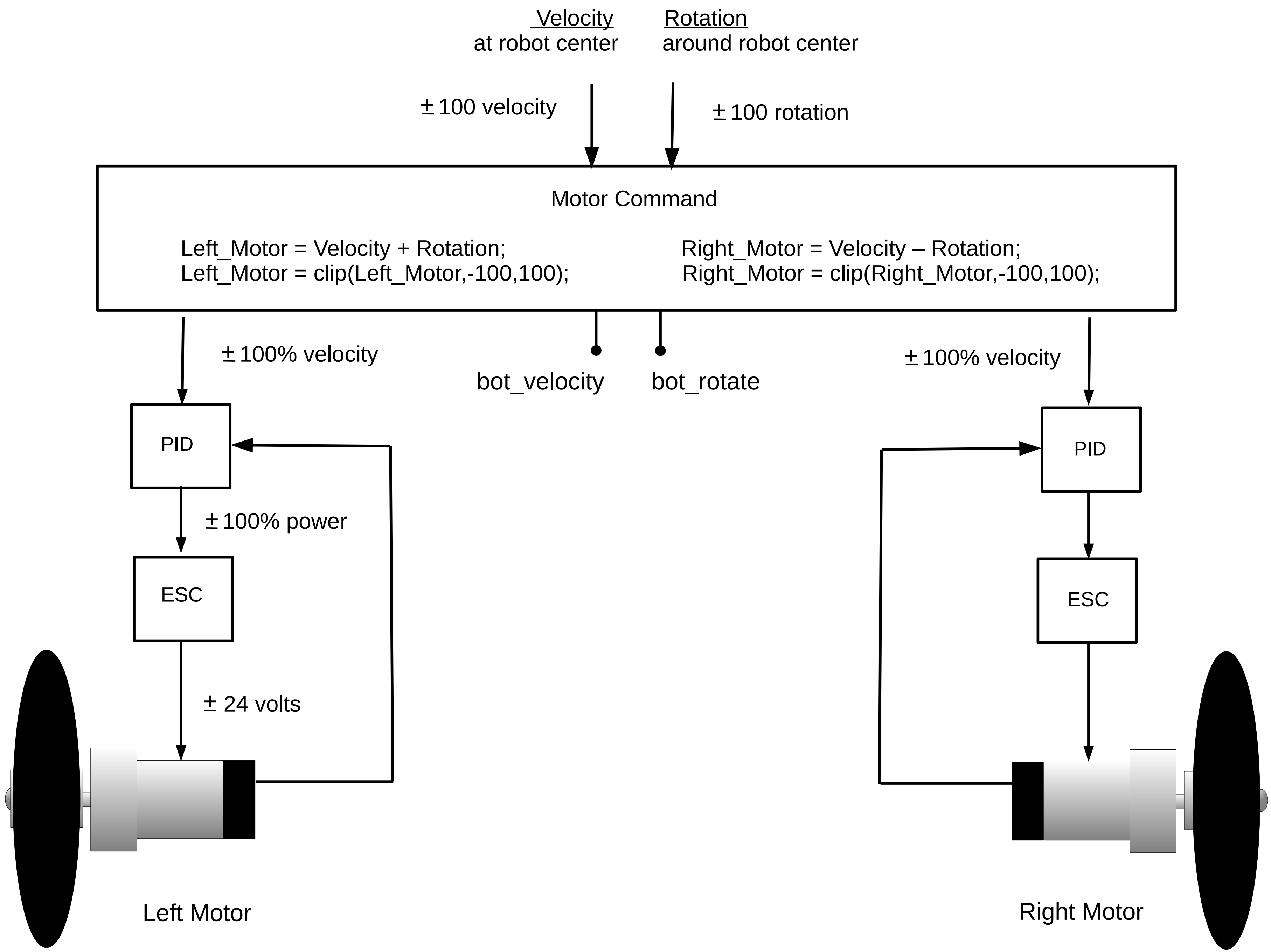
Closed loop control
25 Hz Continuous Message



Closed loop control
25 Hz Continuous Message


Left Motor
Right Motor
± 100% velocity
PID
± 100% power
ESC
± 24 volts
± 100% velocity
PID
ESC

Motor Control Subsystem



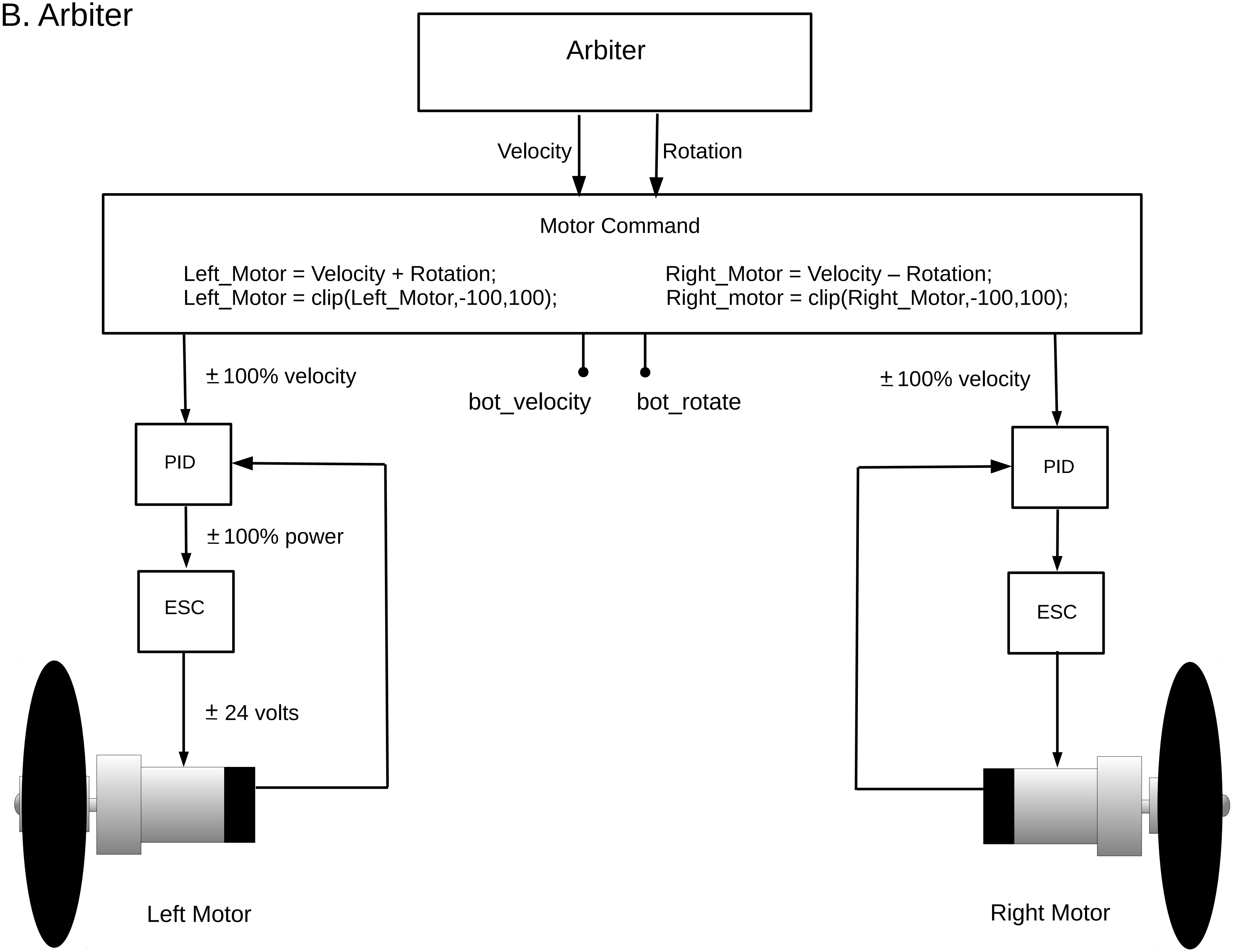
Clip() to minimum and maximum range.

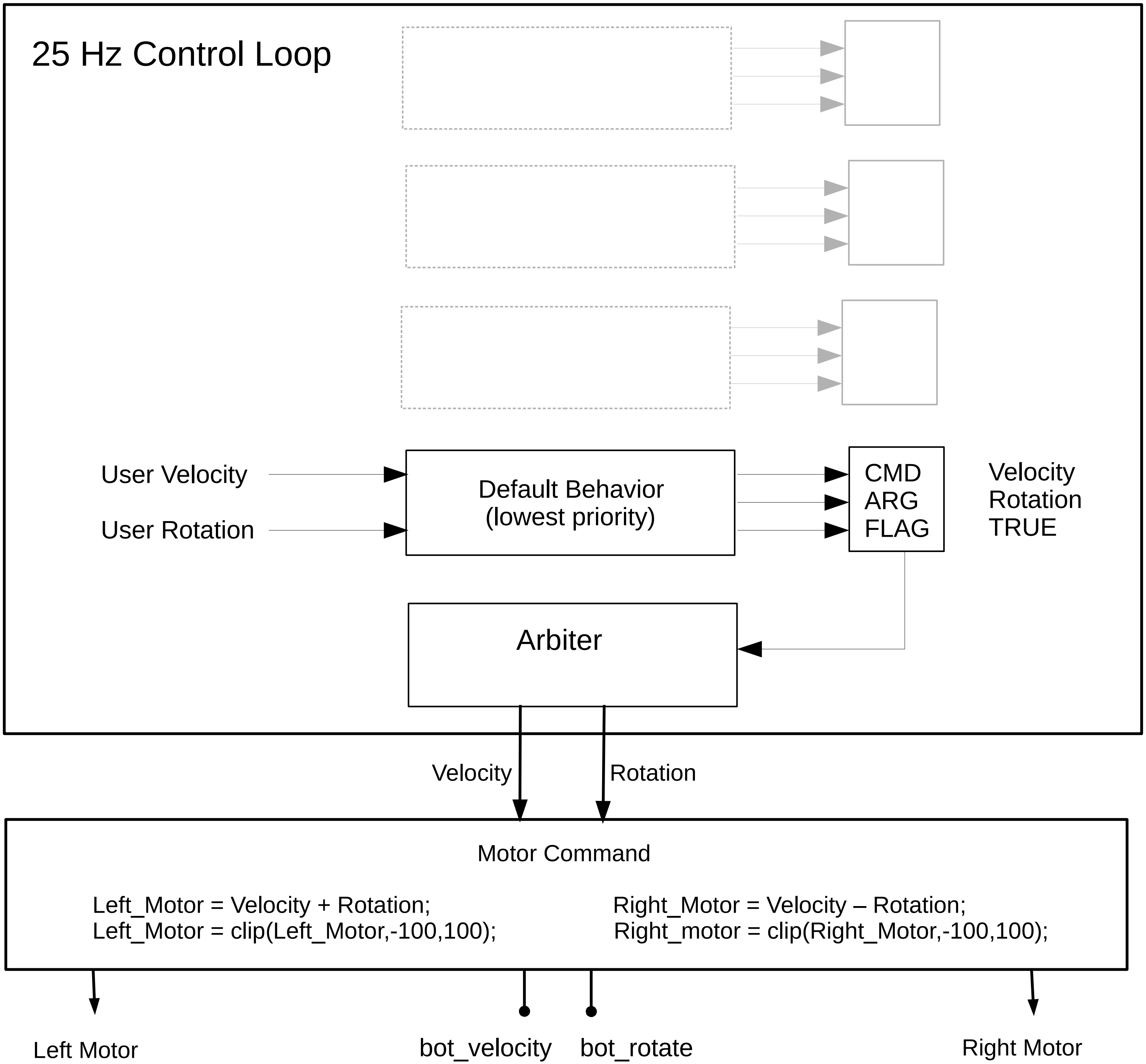
```
float clip ( value, min, max )
{
	if ( value > max ) return max;
	if ( value < min ) return min;
	return value;
}
```

Demo 1

Live
RCAT: Velocity and Rotation

B. Arbiter


Arbiter
Velocity
Rotation
Motor Command
Left_Motor = Velocity + Rotation;
Left_Motor = clip(Left_Motor,-100,100);
Right_Motor = Velocity – Rotation;
Right_motor = clip(Right_Motor,-100,100);
± 100% velocity
bot_velocity
bot_rotate
± 100% velocity
PID
± 100% power
ESC
± 24 volts
Left Motor
PID
ESC
Right Motor


25 Hz Control Loop
User Velocity
User Rotation
Default Behavior
(lowest priority)
CMD
ARG
FLAG
Velocity
Rotation
TRUE
Arbiter
Velocity
Rotation
Motor Command
Left_Motor = Velocity + Rotation;
Left_Motor = clip(Left_Motor,-100,100);
Right_Motor = Velocity – Rotation;
Right_motor = clip(Right_Motor,-100,100);
Left Motor
bot_velocity
bot_rotate
Right Motor

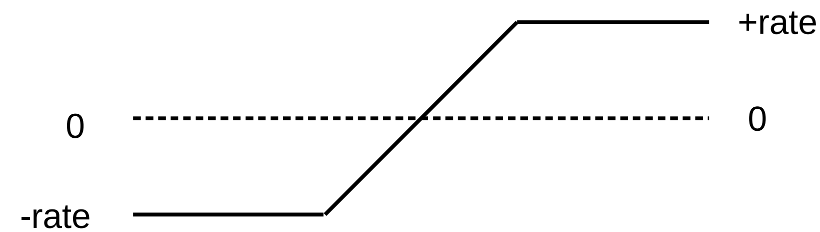
```
typedef struct cmdblock CMDBLOCK;

struct cmdblock
{
        float cmd;      // velocity
        float arg;      // rotation
        int flag;       // execute
}
```

```
CMDBLOCK default;                  // output block for arbiter

void default_behavior( void )      // 25 Hz behavior
{
        default.cmd = p_user_velocity;
        default.arg  = p_user_rotate;
        default.flag  = TRUE;
}
```

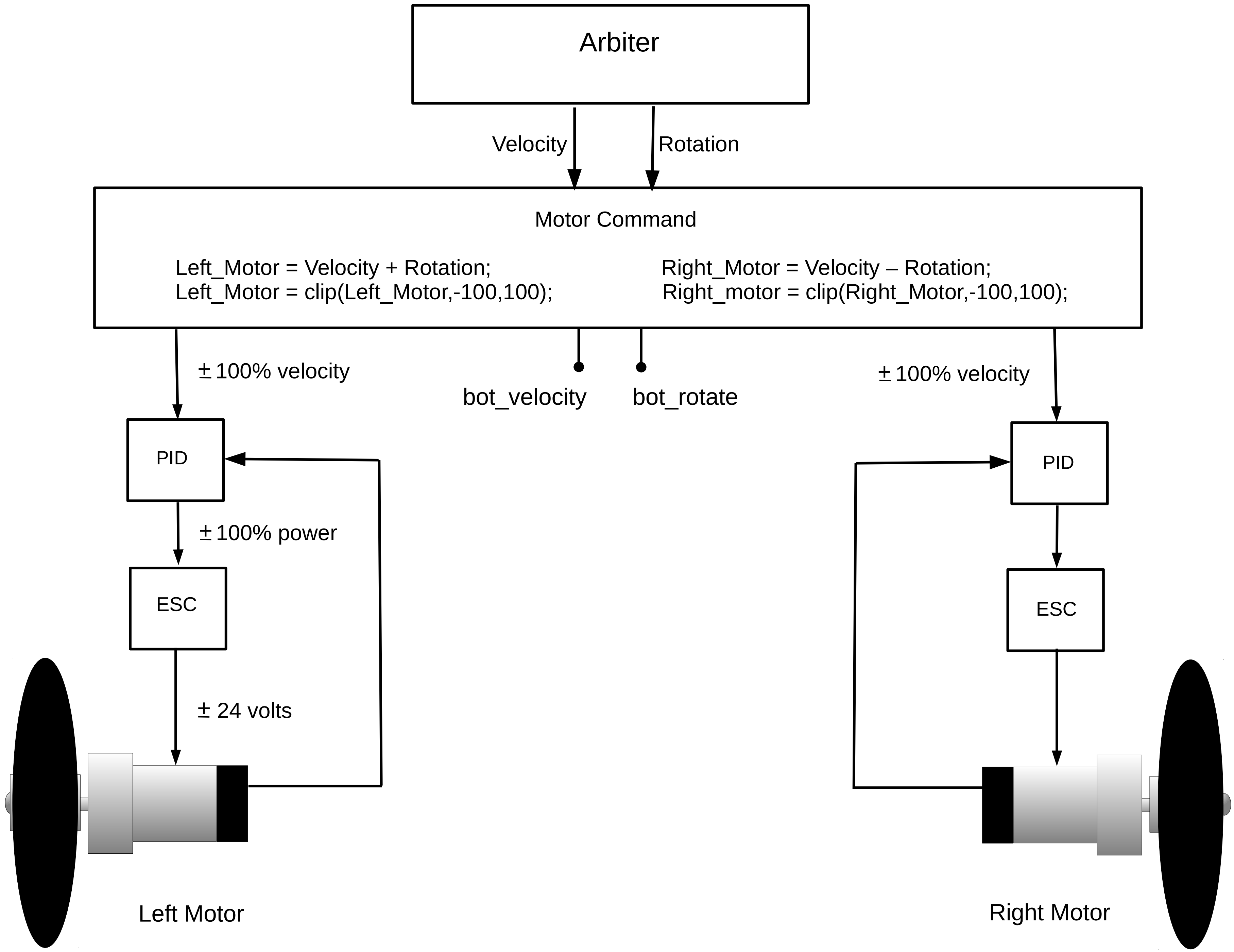
```
CMDBLOCK default;

void default_behavior ( void )
{
	default.cmd = slew_vel ( p_user_velocity, p_user_vrate );
	default.arg  = slew_rot (  p_user_rotate, p_user_rrate );
	default.flag  = TRUE;
}
```

```
void default_behavior ( void )
{
      default.cmd = slew_vel ( p_user_velocity, p_user_vrate );
      default.arg  = slew_rot (  p_user_rotate, p_user_rrate );
      default.flag  = TRUE;
}
```

```
float slew ( float from, to, rate )
{
      float dif = to – from;
      if (dif > rate)  return (from + rate);
      if (dif < -rate) return (from – rate);
      return to;
}
```



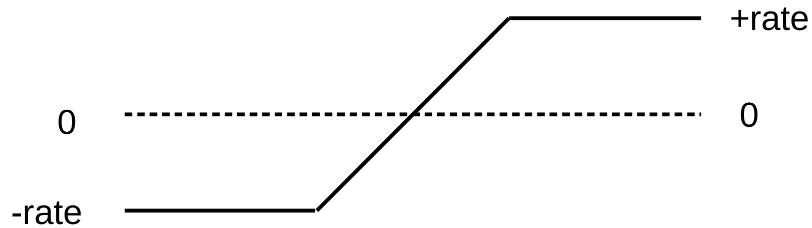
Slew Rate Limiter


Arbiter
Velocity
Rotation
Motor Command
Left_Motor = Velocity + Rotation;
Left_Motor = clip(Left_Motor,-100,100);
Right_Motor = Velocity – Rotation;
Right_motor = clip(Right_Motor,-100,100);
± 100% velocity
bot_velocity
bot_rotate
± 100% velocity
PID
PID
± 100% power
ESC
ESC
± 24 volts
Left Motor
Right Motor

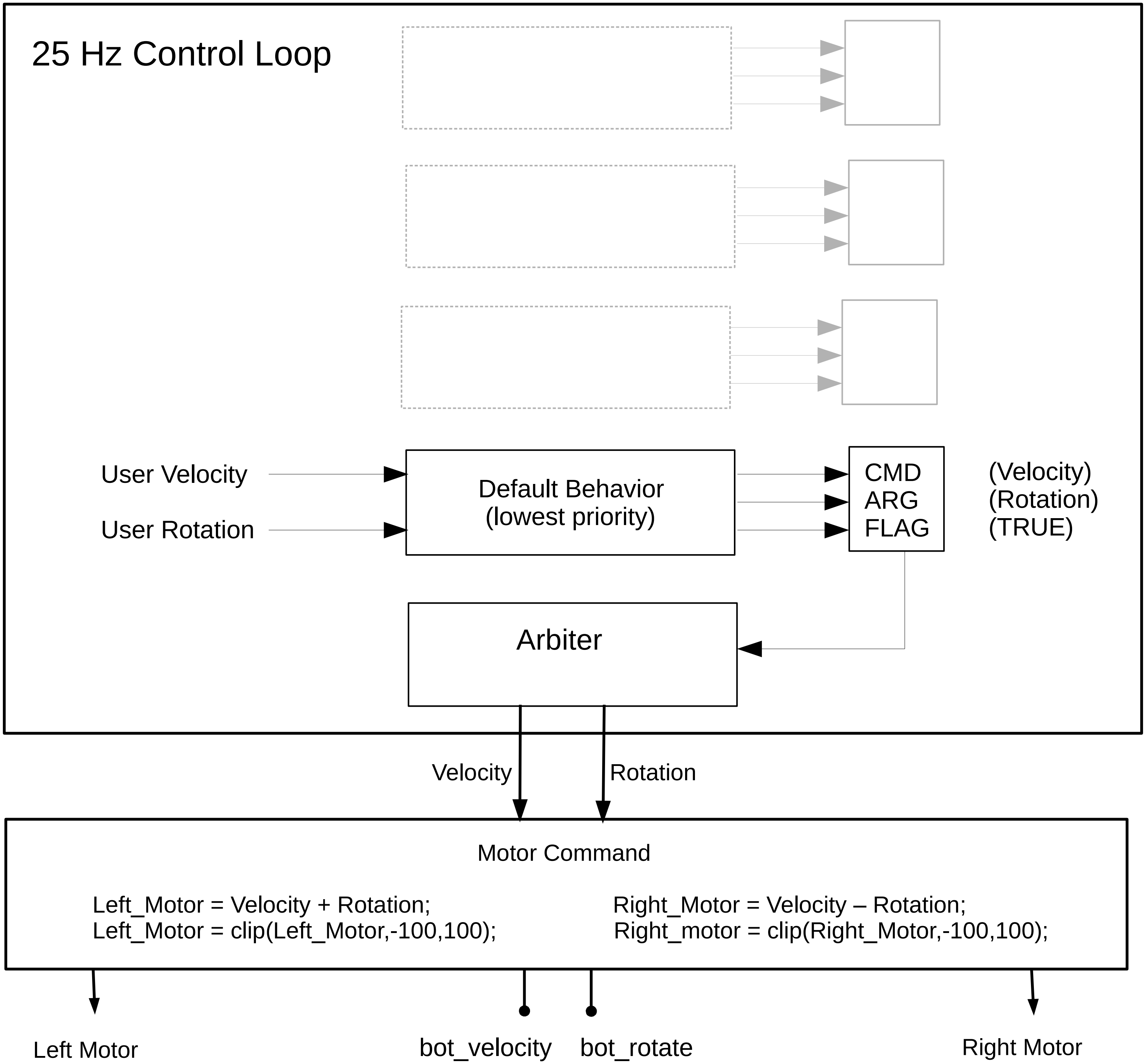
```
void default_behavior (void)
{
      default.cmd = slew_vel ( p_user_velocity, p_user_vrate );
      default.arg  = slew_rot (  p_user_rotate, p_user_rrate );
      default.flag  = TRUE;
}
```

```
float slew ( float from, to, rate )
{
      float dif = to – from;
      if (dif > rate)  return (from + rate);
      if (dif < -rate) return (from – rate);
      return to;
}
```

```
float slew_vel ( float to, rate )
{
      return slew ( bot_velocity, to, rate );
}

float slew_rot ( float to, rate )
{
      return slew ( bot_rotate, to, rate );
}
```

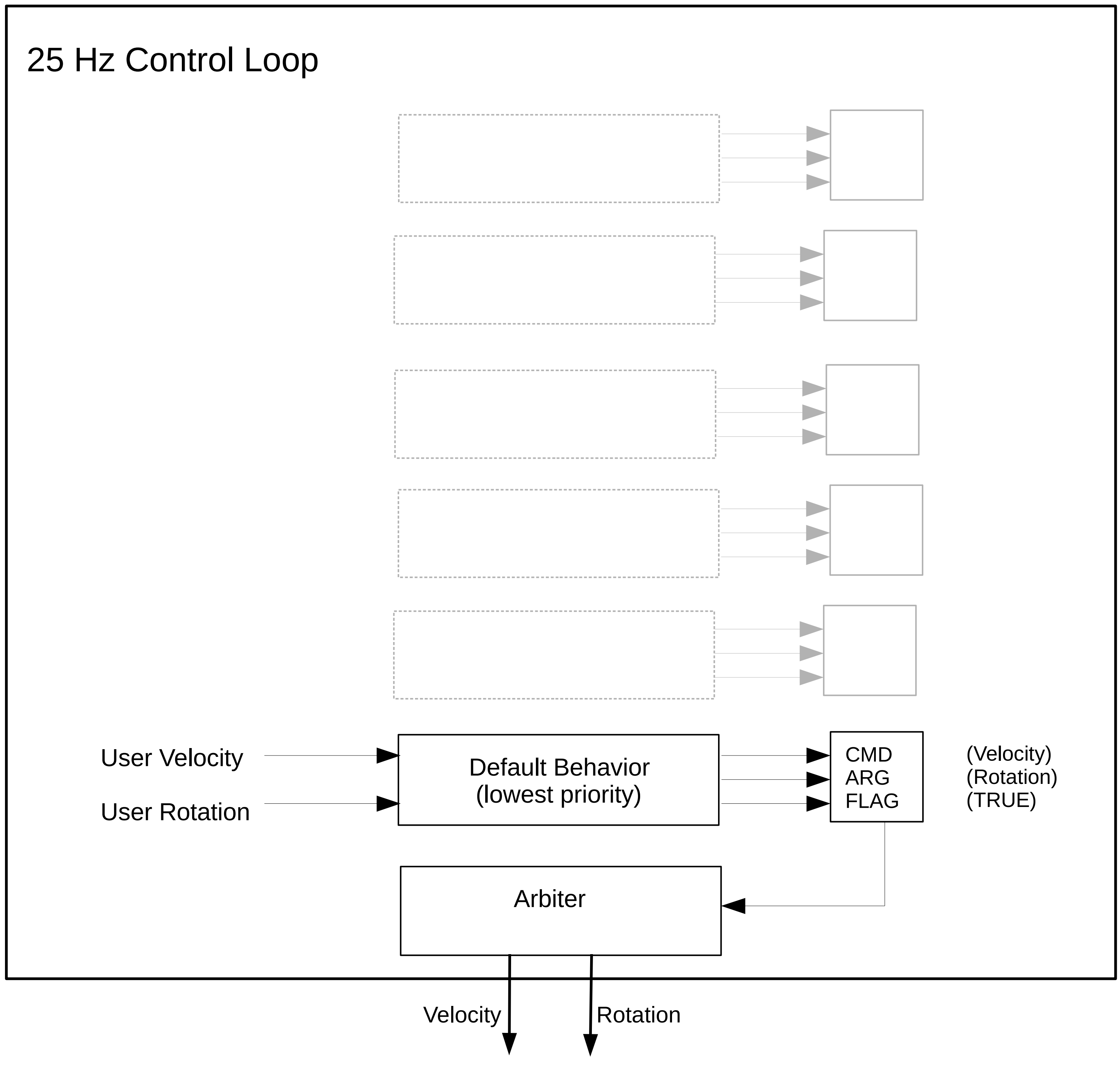


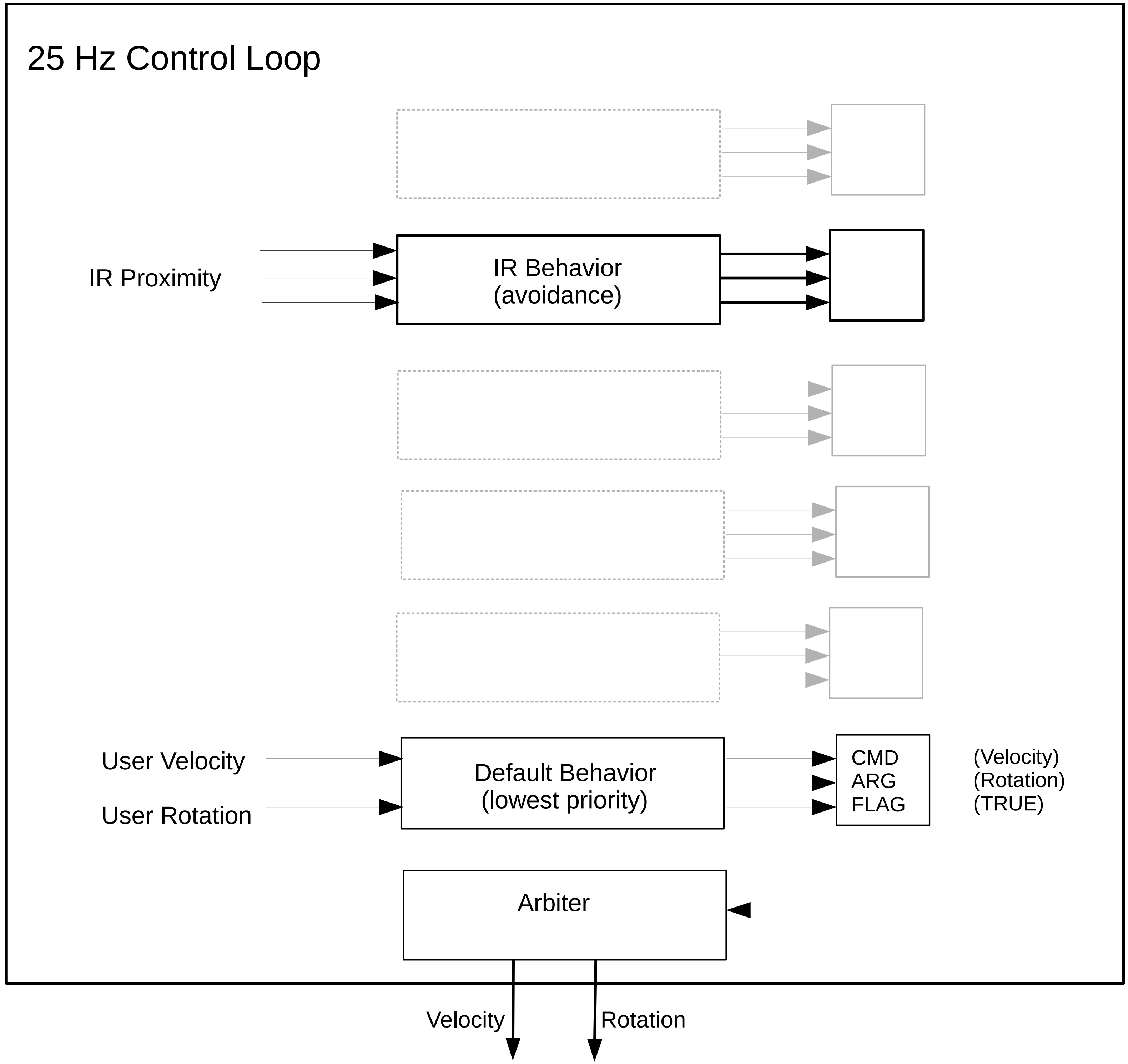
Slew Rate Limiter


25 Hz Control Loop
User Velocity
User Rotation
Default Behavior
(lowest priority)
CMD
ARG
FLAG
(Velocity)
(Rotation)
(TRUE)
Arbiter
Velocity
Rotation
Motor Command
Left_Motor = Velocity + Rotation;
Left_Motor = clip(Left_Motor,-100,100);
Right_Motor = Velocity – Rotation;
Right_motor = clip(Right_Motor,-100,100);
Left Motor
bot_velocity
bot_rotate
Right Motor

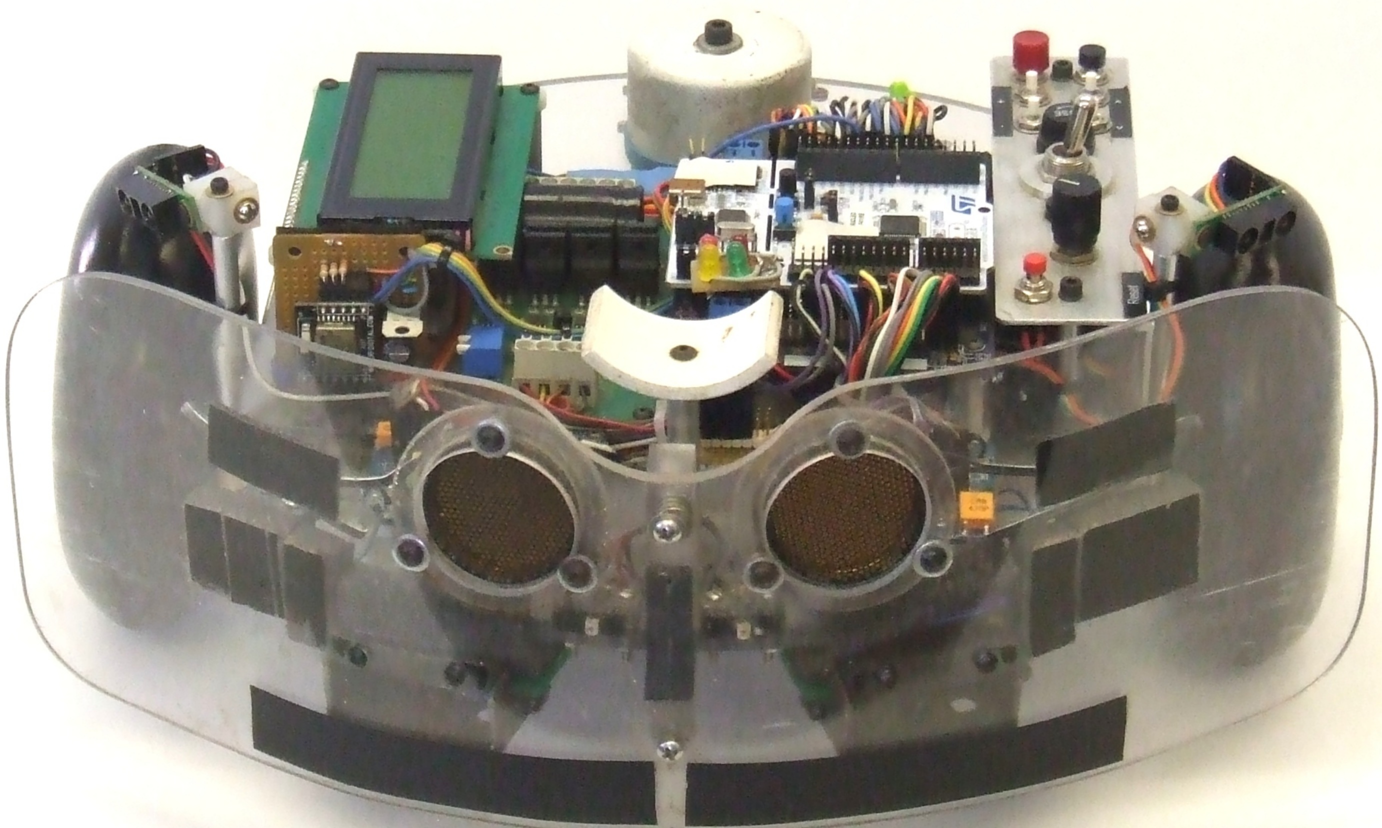
Demo 2

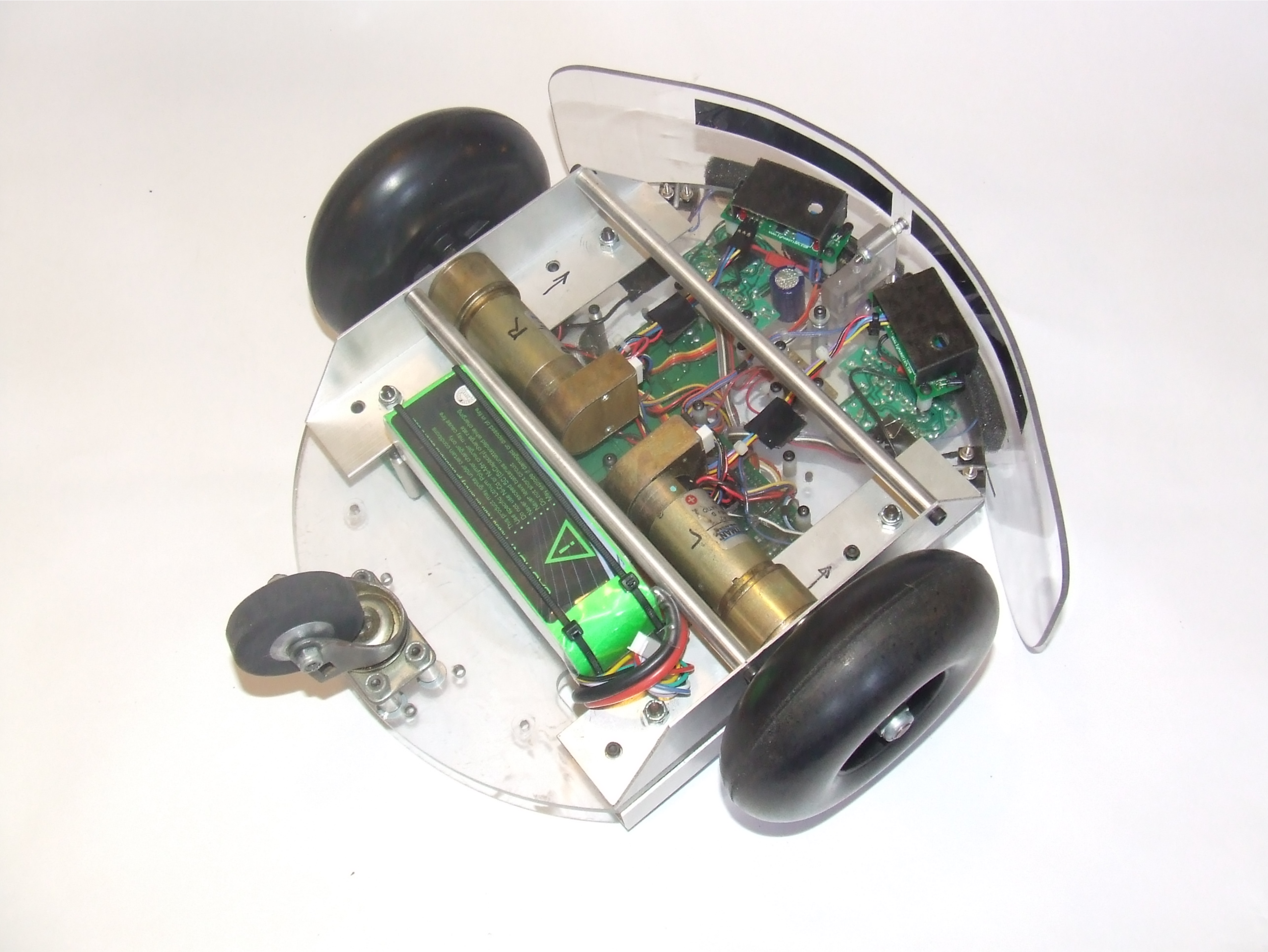
Live
RCAT: Slew Rates


25 Hz Control Loop
User Velocity
User Rotation
Default Behavior
(lowest priority)
CMD
ARG
FLAG
(Velocity)
(Rotation)
(TRUE)
Arbiter
Velocity
Rotation

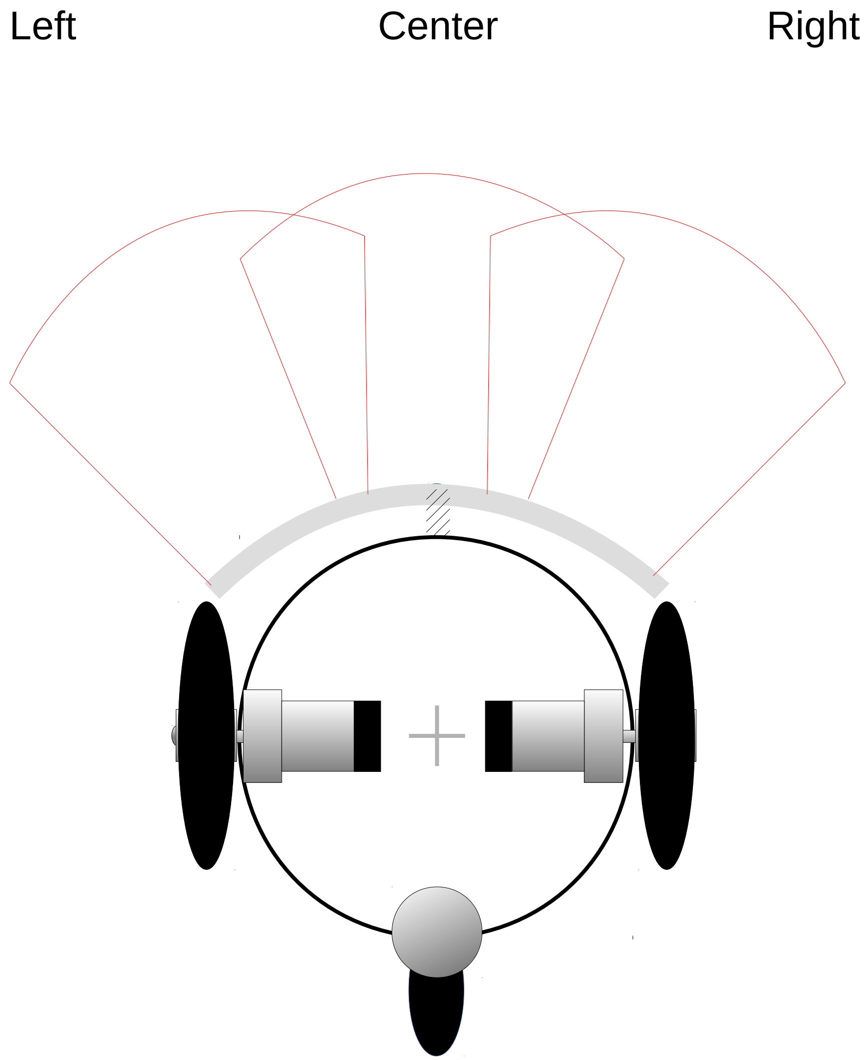


25 Hz Control Loop
IR Proximity
IR Behavior
(avoidance)
User Velocity
User Rotation
Default Behavior
(lowest priority)
CMD
ARG
FLAG
(Velocity)
(Rotation)
(TRUE)
Arbiter
Velocity
Rotation





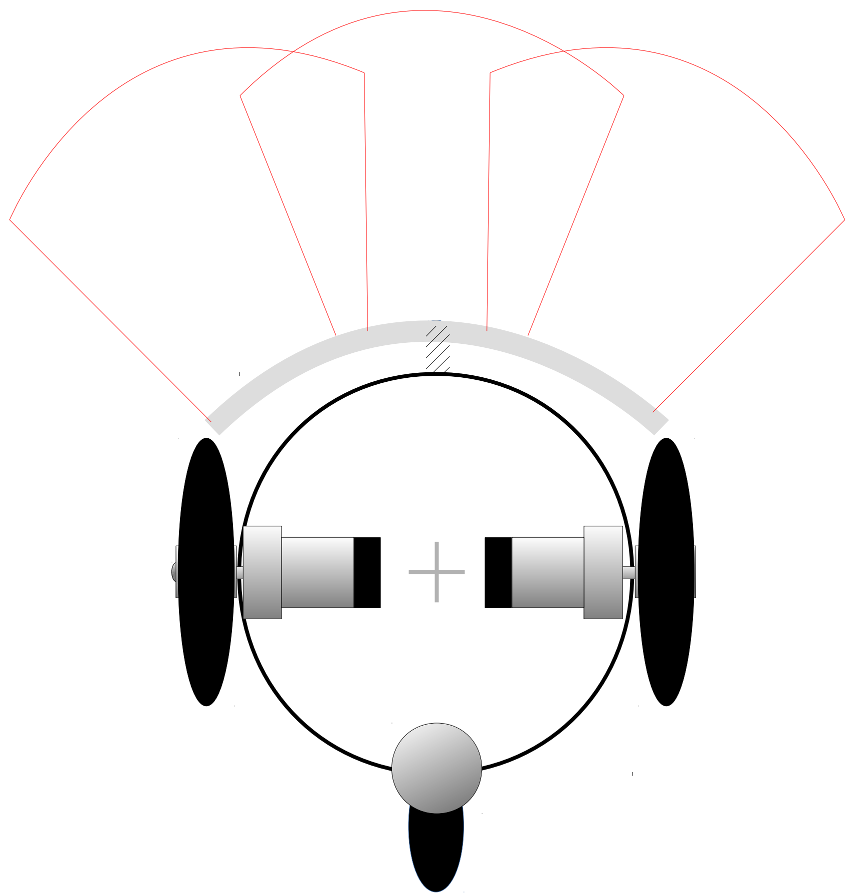
IR Proximity Detectors



IR Proximity Detectors

ir_read()

1	4	2
Left	Center	Right



IR Behavior

Call ir_read()

If NO detect, exit.

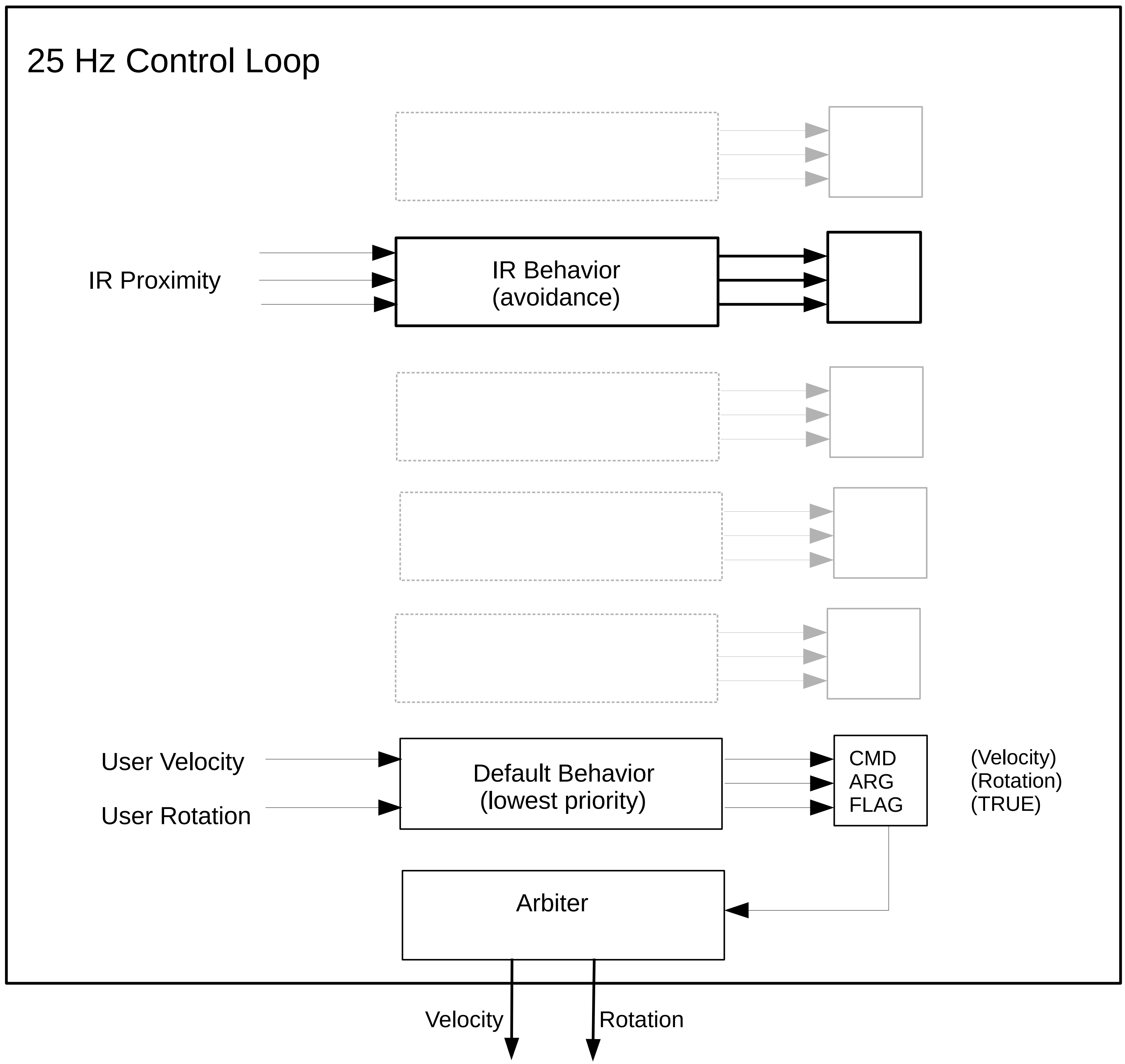
If LEFT detect, slow down, turn right.

If RIGHT detect, slow down, turn left.

If CENTER detect, slow to 0, keep turning...

```
// The PID controllers maintain left_velocity and right_velocity,
// and also left_avg_velocity and right_avg_velocity ( ~1.25s moving window )


int keep_turning ( int avg_flag )
{
        if ( avg_flag )   {          // use average velocity
                if ( left_avg_velocity > right_avg_velocity ) return 1;
                else return -1;
        }                                        // else use instantaneous velocity
        if ( left_velocity > right_velocity ) return 1;
        return -1
}
```

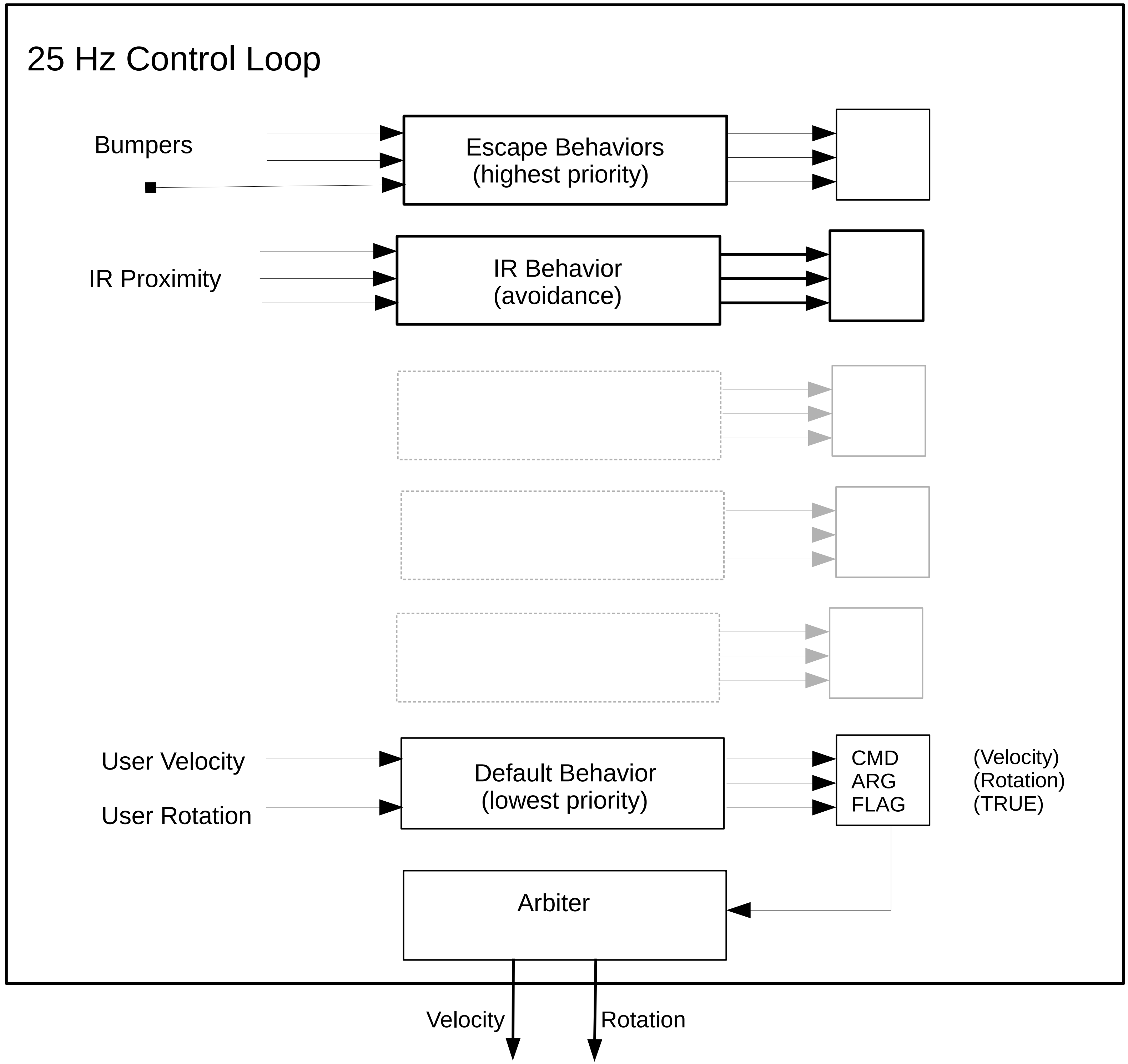
```
CMDBLOCK ir;                               // output struct for arbiter()

void IR_Behavior( void )
{
   int detect = read_ir();                 // read IR sensors, 0 = NO DETECT,
                                           //  1 = LEFT, 2 = RIGHT, 4 = CENTER
   If ( detect == 0 )
        ir.flag = FALSE;                   // and exit
   else
   {    ir.flag = TRUE;
        if ( detect > 2 ) detect = CENTER;

        switch ( detect ) {

           case LEFT : {                   // left detect, slow to ½ speed
                                           // and turn right
                ir.cmd = slew_vel ( p_user_velocity/2, p_ir_vrate );
                ir.arg = slew_rot ( p_ir_turn, p_ir_rrate );
                break;
           }

           case RIGHT : {                  // right detect, slow to ½ speed
                                           // and turn left
                ir.cmd = slew_vel ( p_user_velocity/2, p_ir_vrate );
                ir.arg = slew_rot ( -p_ir_turn, p_ir_rrate );
                break;
           }

           case CENTER : {                 // center detect, slow to 0
                                           // and keep turning the "same" direction
                ir.cmd = slew_vel ( 0, p_ir_vrate );
                ir.arg = slew_rot ( p_ir_turn * keep_turning ( 0 ),  p_ir_rrate );
                break;
           }
        }
    }
}
```

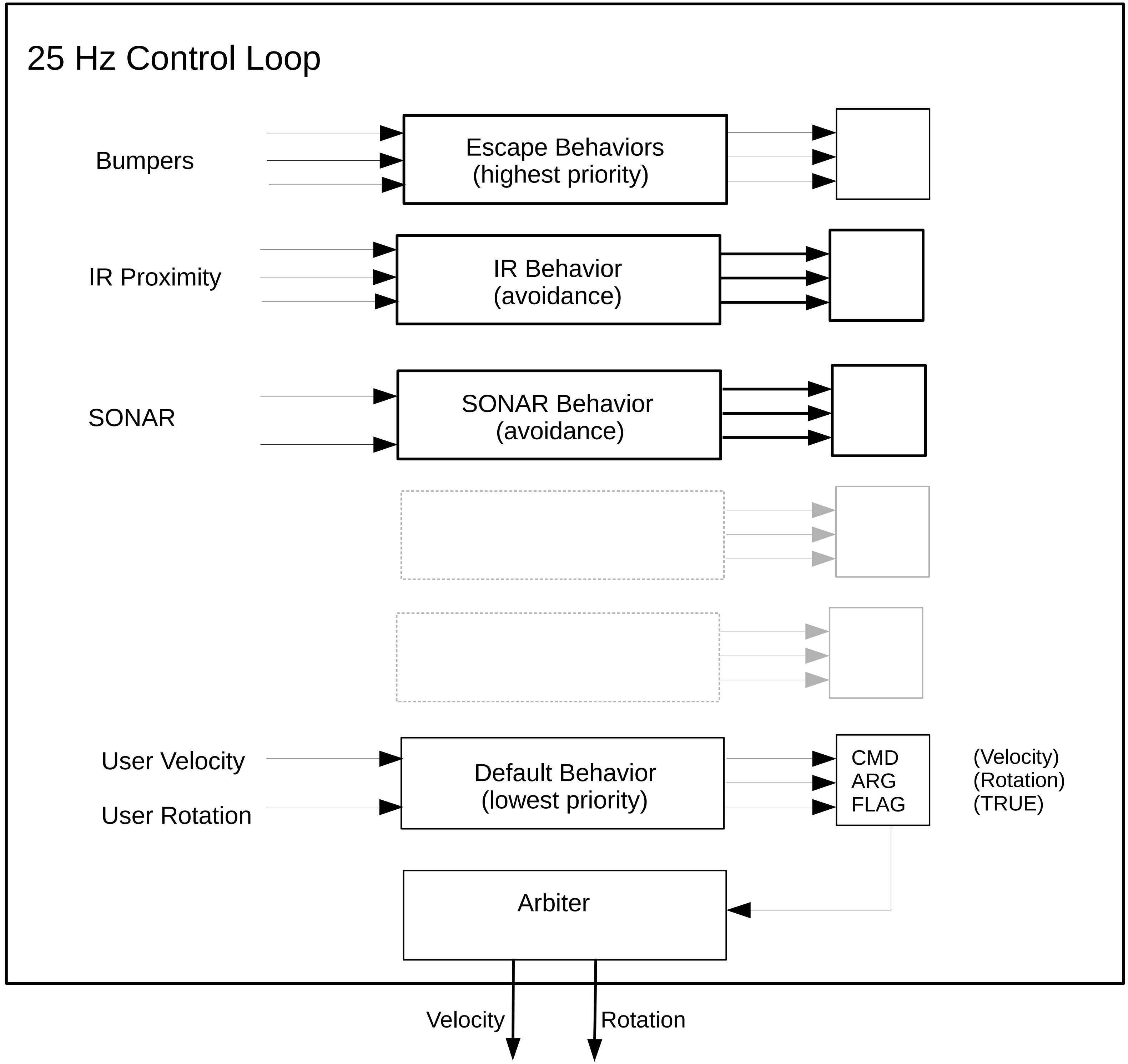


25 Hz Control Loop
IR Proximity
IR Behavior
(avoidance)
User Velocity
User Rotation
Default Behavior
(lowest priority)
CMD
ARG
FLAG
(Velocity)
(Rotation)
(TRUE)
Arbiter
Velocity
Rotation

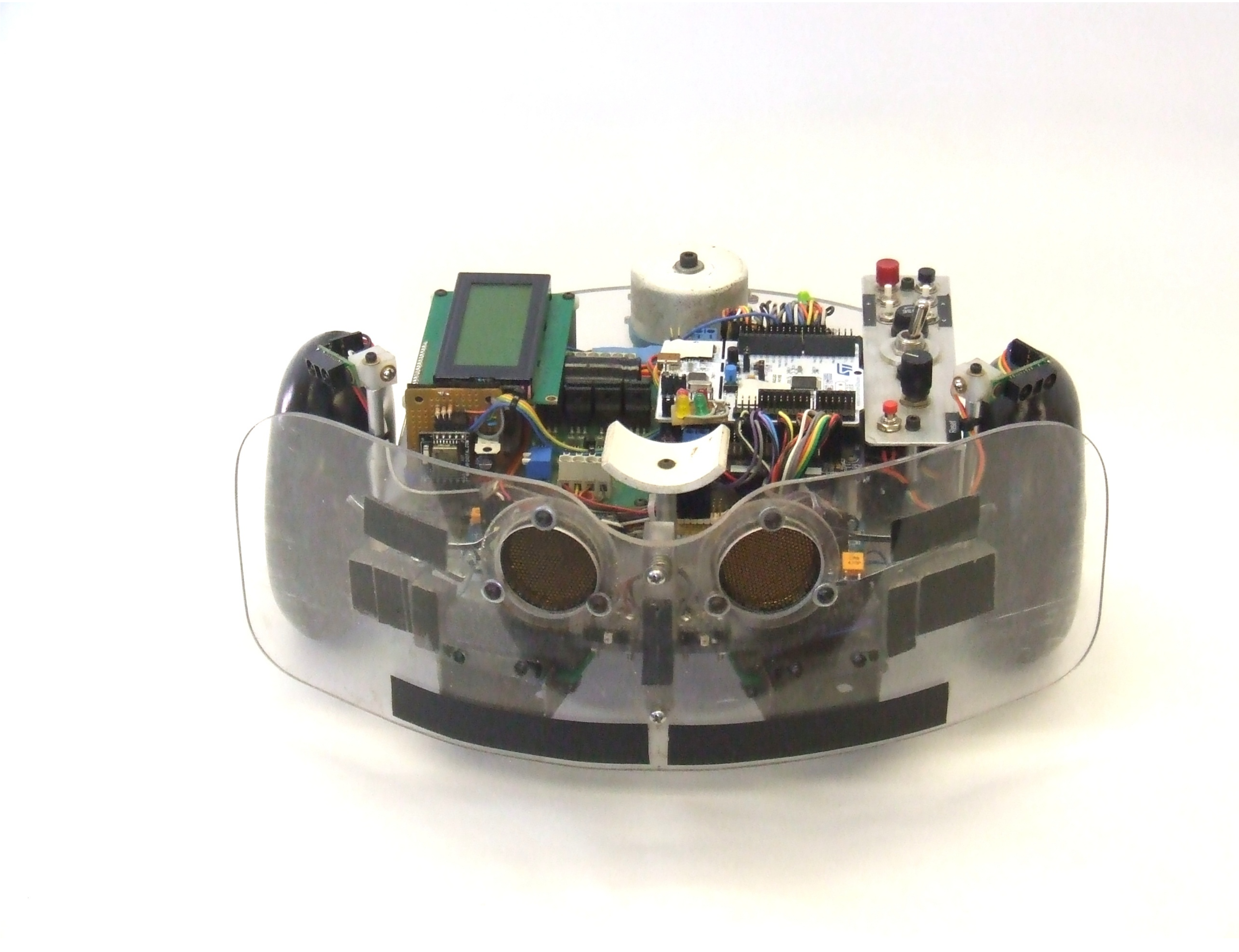
Demo 3

Live
RCAT: IR Avoidance

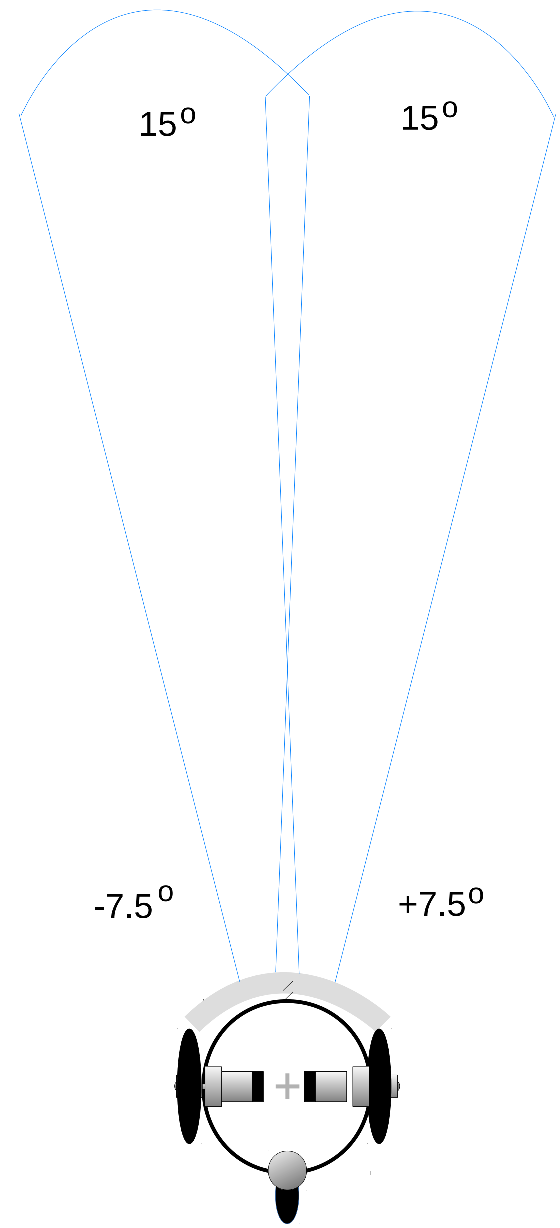

25 Hz Control Loop
Bumpers
Escape Behaviors
(highest priority)
IR Proximity
IR Behavior
(avoidance)
User Velocity
User Rotation
Default Behavior
(lowest priority)
CMD
ARG
FLAG
(Velocity)
(Rotation)
(TRUE)
Arbiter
Velocity
Rotation



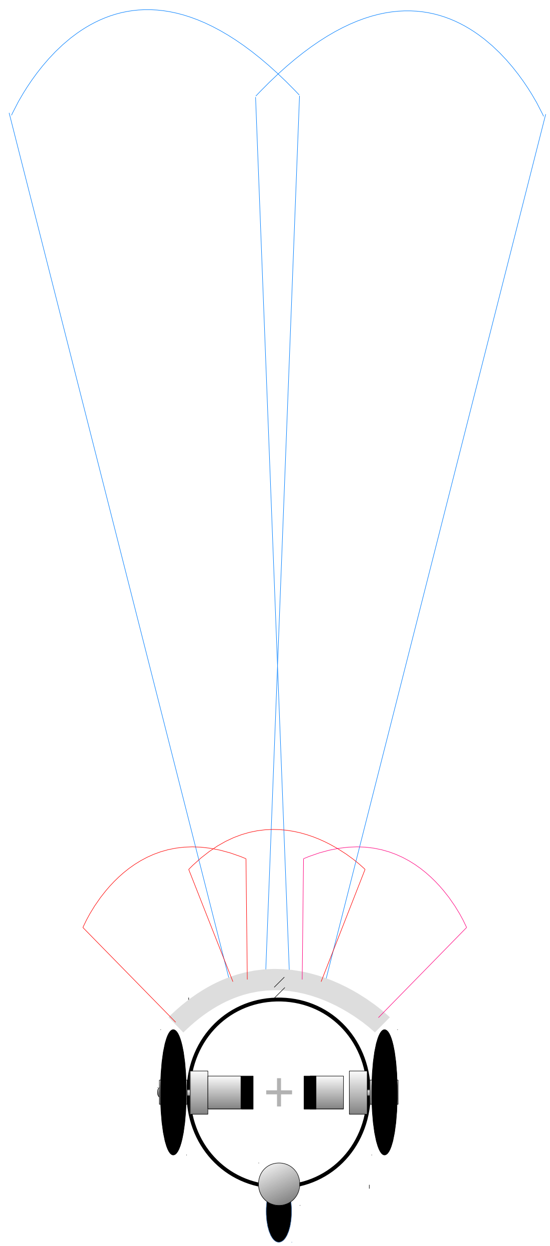
25 Hz Control Loop
Bumpers
Escape Behaviors
(highest priority)
IR Proximity
IR Behavior
(avoidance)
SONAR
SONAR Behavior
(avoidance)
User Velocity
User Rotation
Default Behavior
(lowest priority)
CMD
ARG
FLAG
(Velocity)
(Rotation)
(TRUE)
Arbiter
Velocity
Rotation



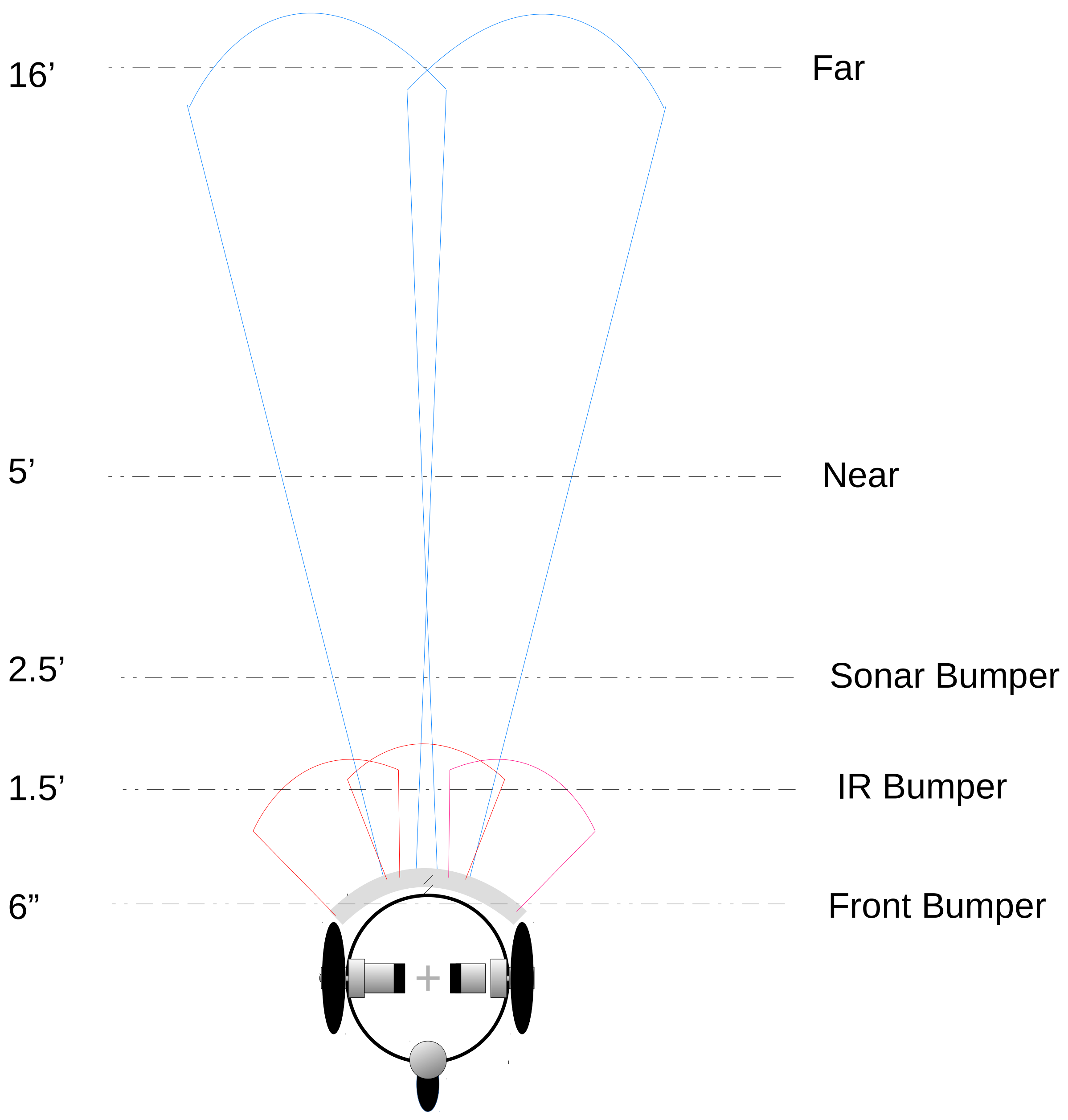
Stereo SONAR

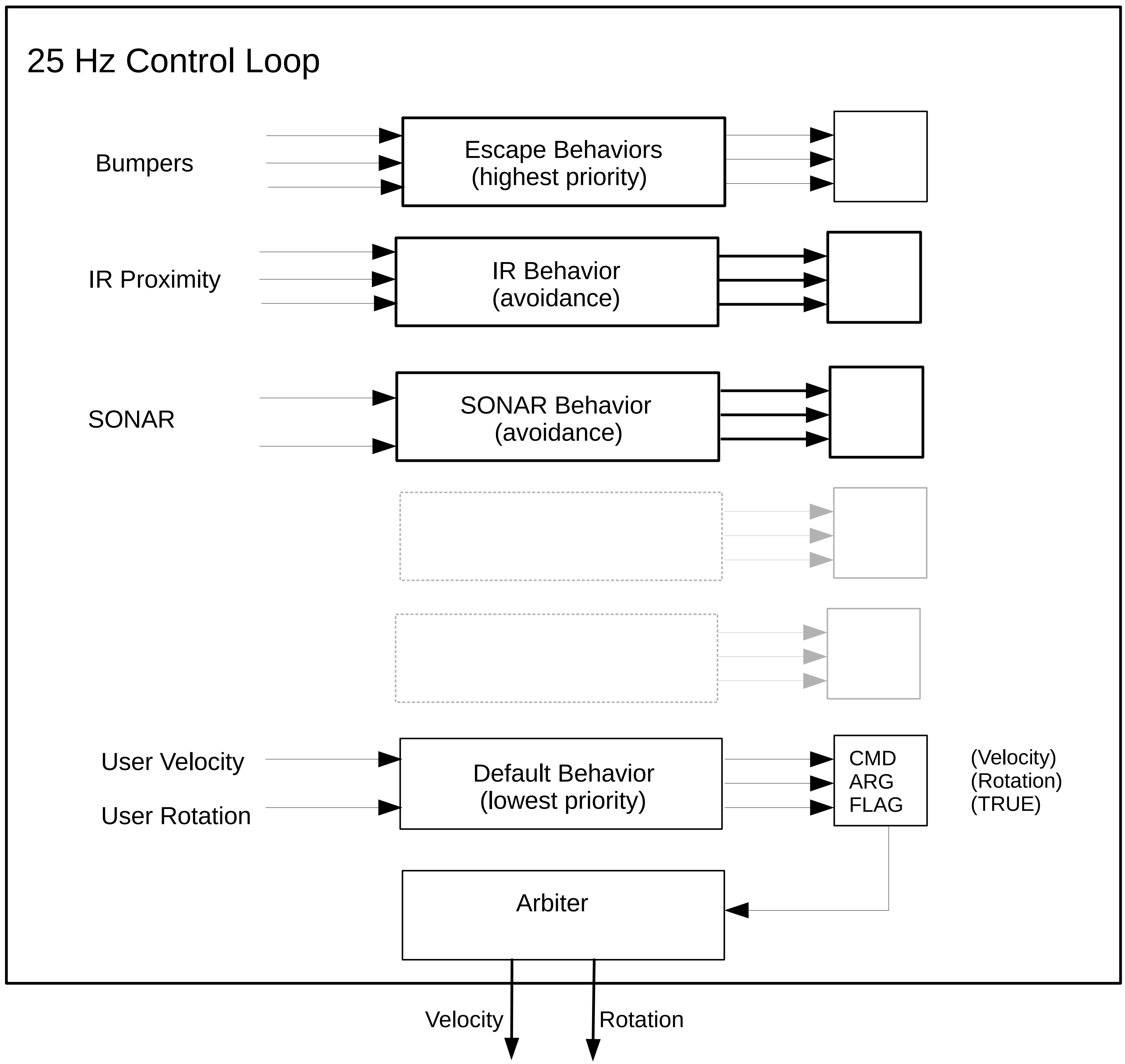


Stereo SONAR, IR Proximity

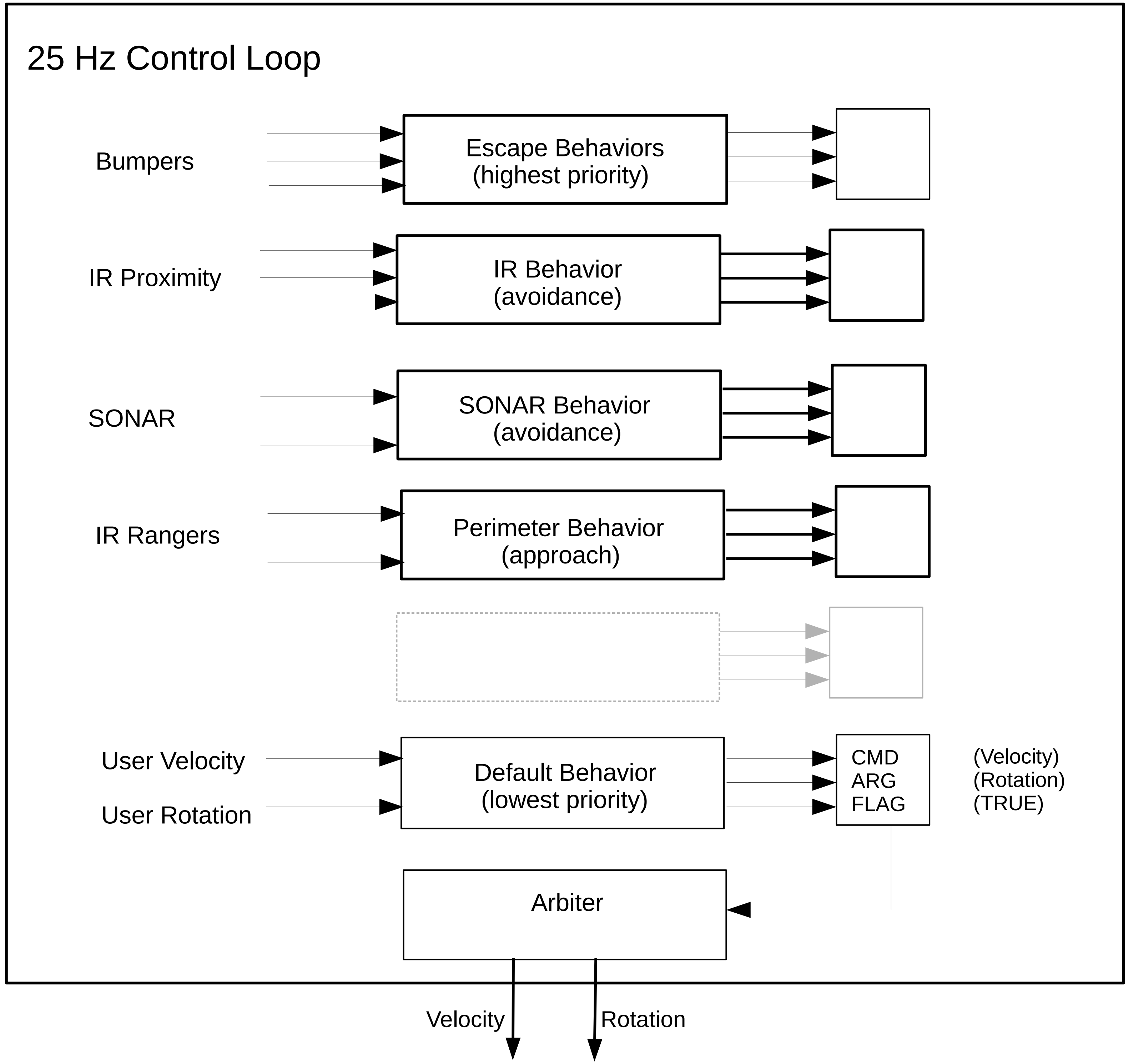


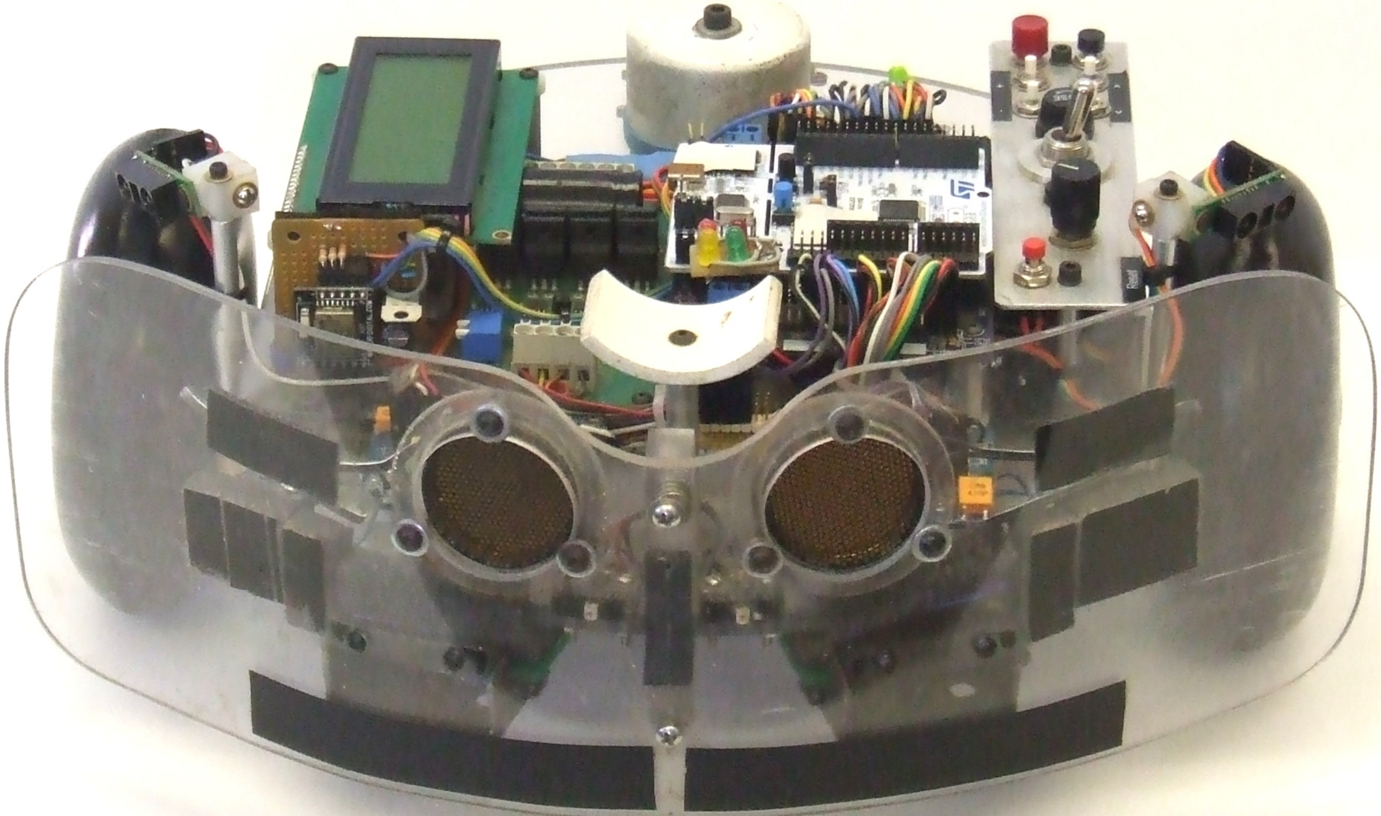
Stereo SONAR, IR Proximity



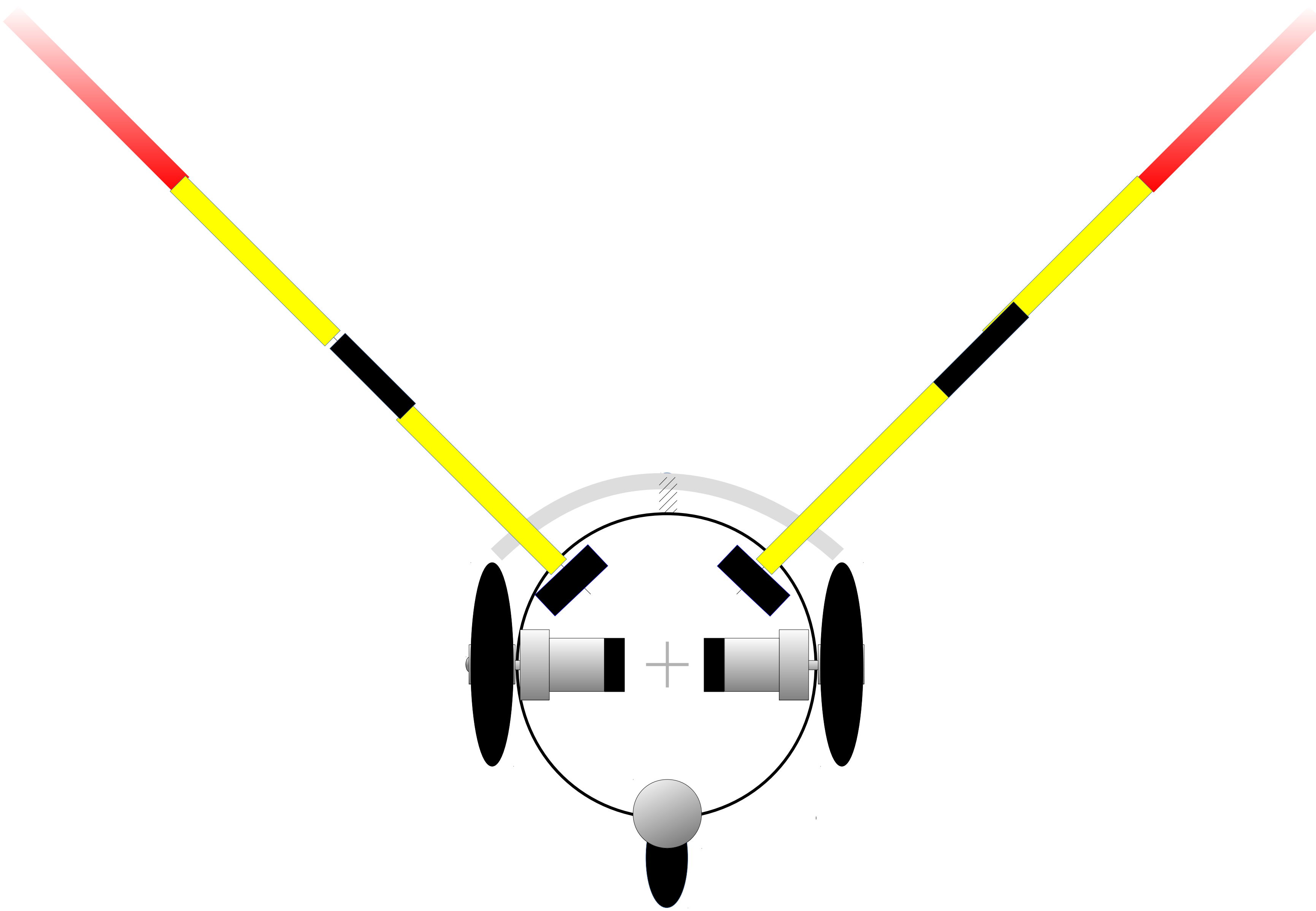


25 Hz Control Loop
Bumpers
Escape Behaviors
(highest priority)
IR Proximity
IR Behavior
(avoidance)
SONAR
SONAR Behavior
(avoidance)
User Velocity
User Rotation
Default Behavior
(lowest priority)
CMD
ARG
FLAG
(Velocity)
(Rotation)
(TRUE)
Arbiter
Velocity
Rotation

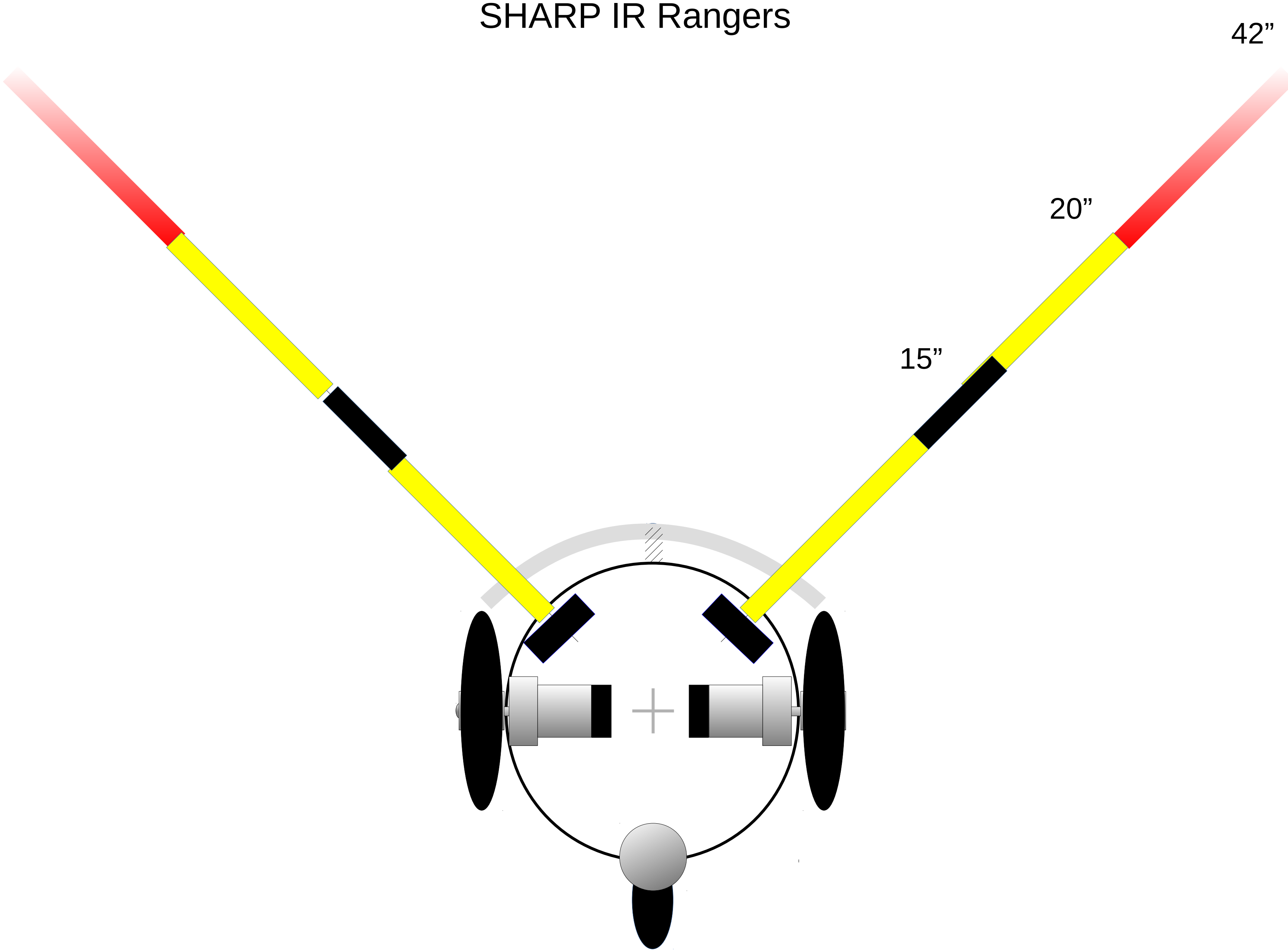

25 Hz Control Loop
Bumpers
Escape Behaviors
(highest priority)
IR Proximity
IR Behavior
(avoidance)
SONAR
SONAR Behavior
(avoidance)
IR Rangers
Perimeter Behavior
(approach)
User Velocity
User Rotation
Default Behavior
(lowest priority)
CMD
ARG
FLAG
(Velocity)
(Rotation)
(TRUE)
Arbiter
Velocity
Rotation

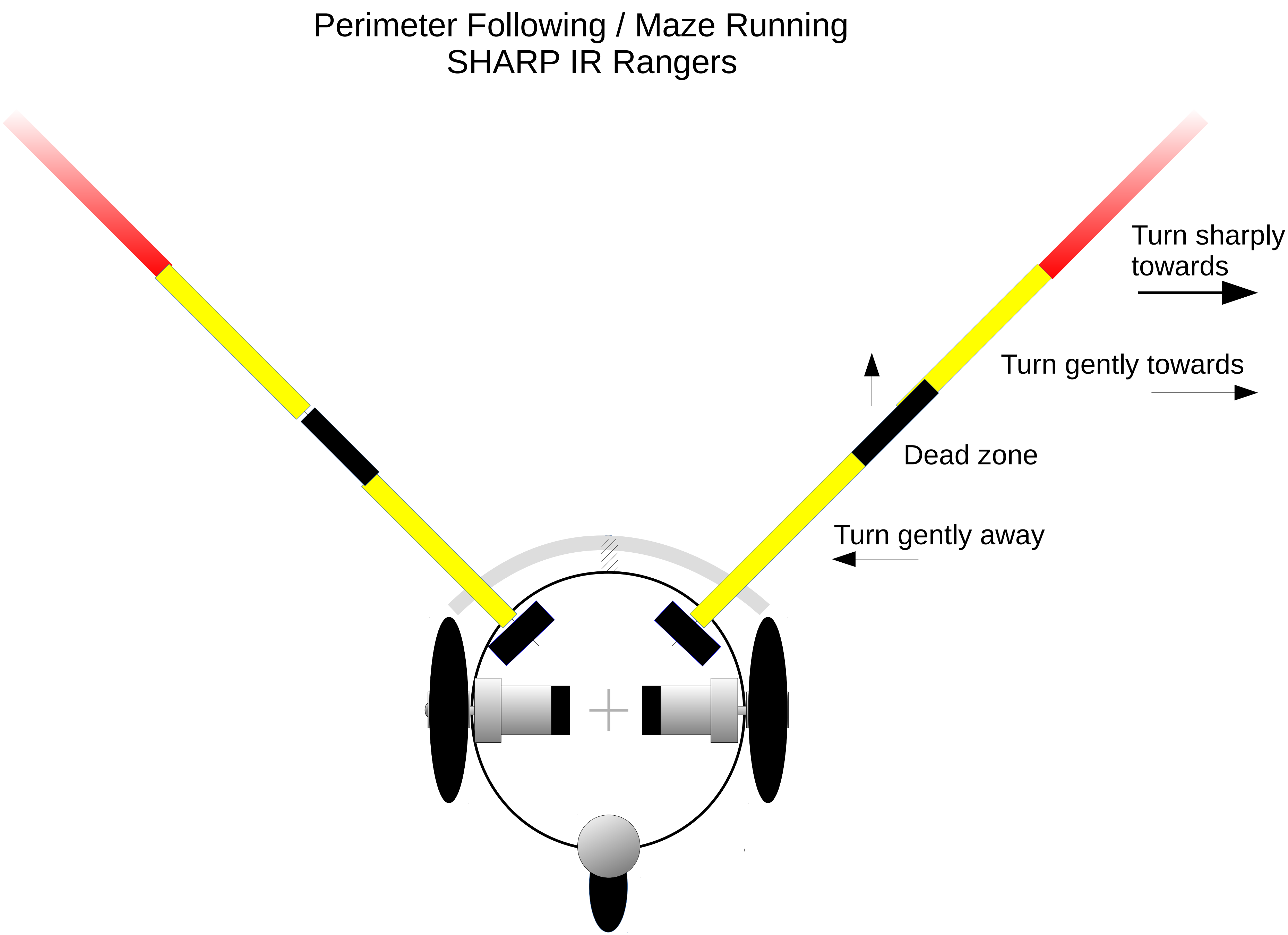


Perimeter Following / Maze Running
SHARP IR Rangers



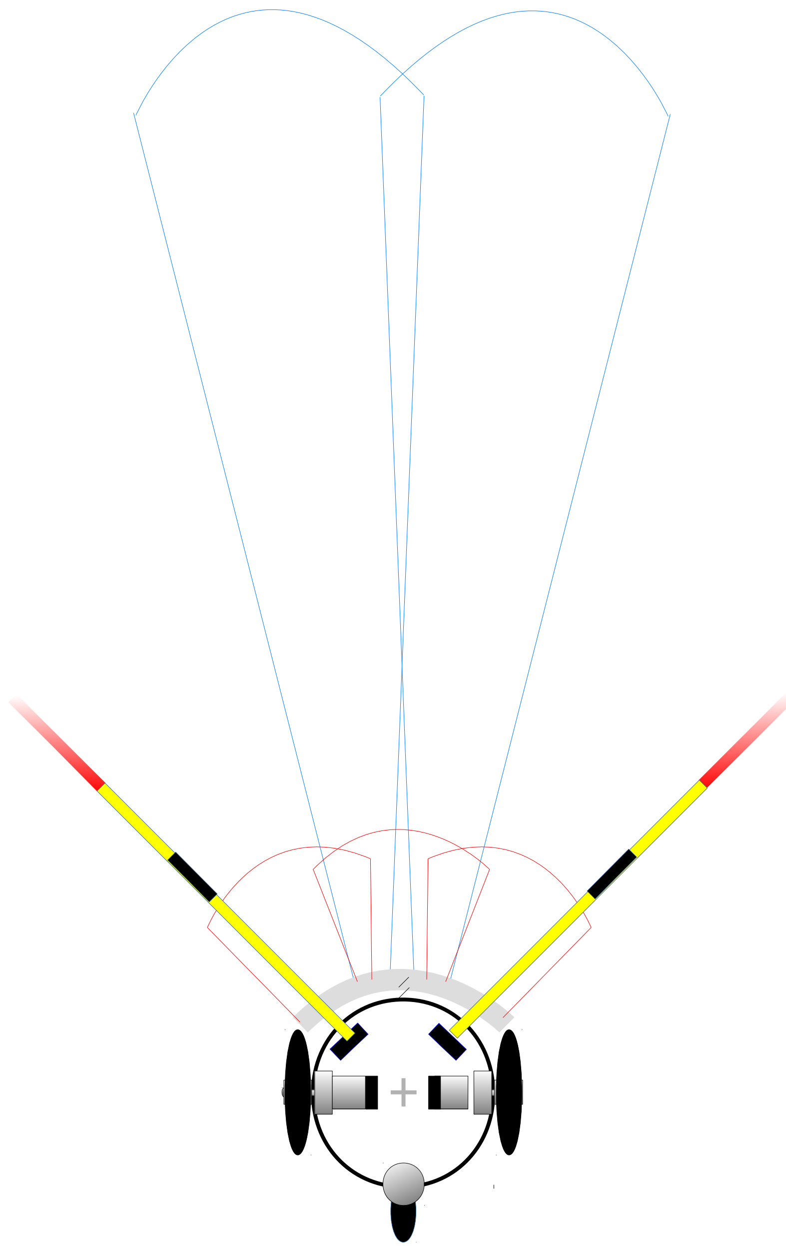
Perimeter Following / Maze Running
SHARP IR Rangers





Perimeter Following / Maze Running
SHARP IR Rangers
Turn sharply
towards
Turn gently towards
Dead zone
Turn gently away

Stereo SONAR, IR Proximity, IR Rangers



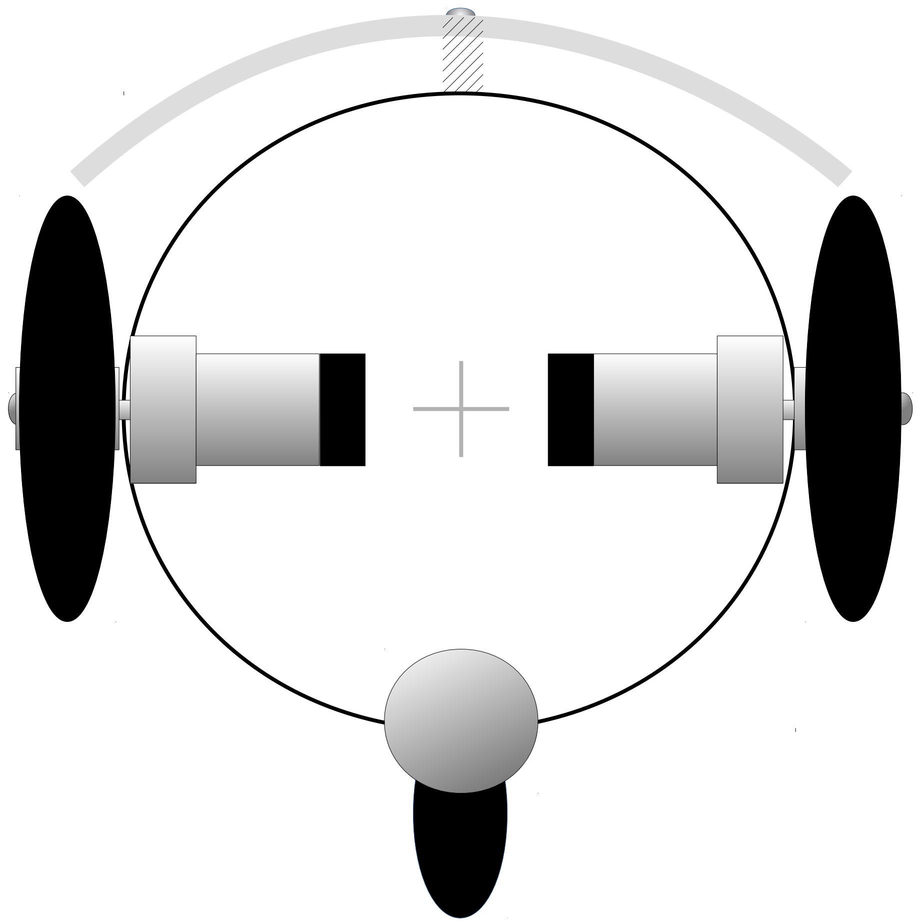
D4

Demo 4

Videos:

RCAT: Perimeter Following
nBot: Perimeter Following

II. Waypoint Navigation



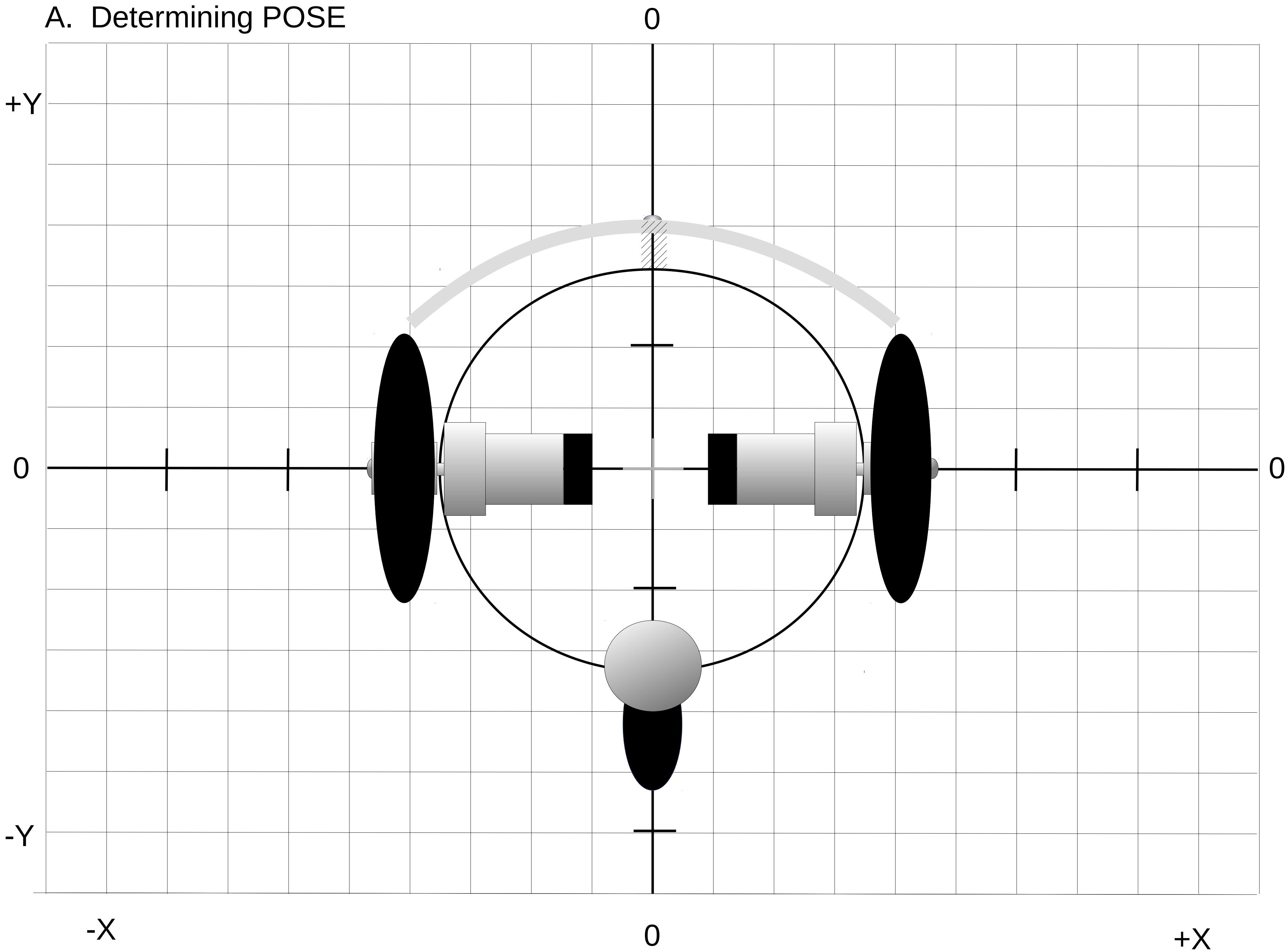
II. Waypoint Navigation

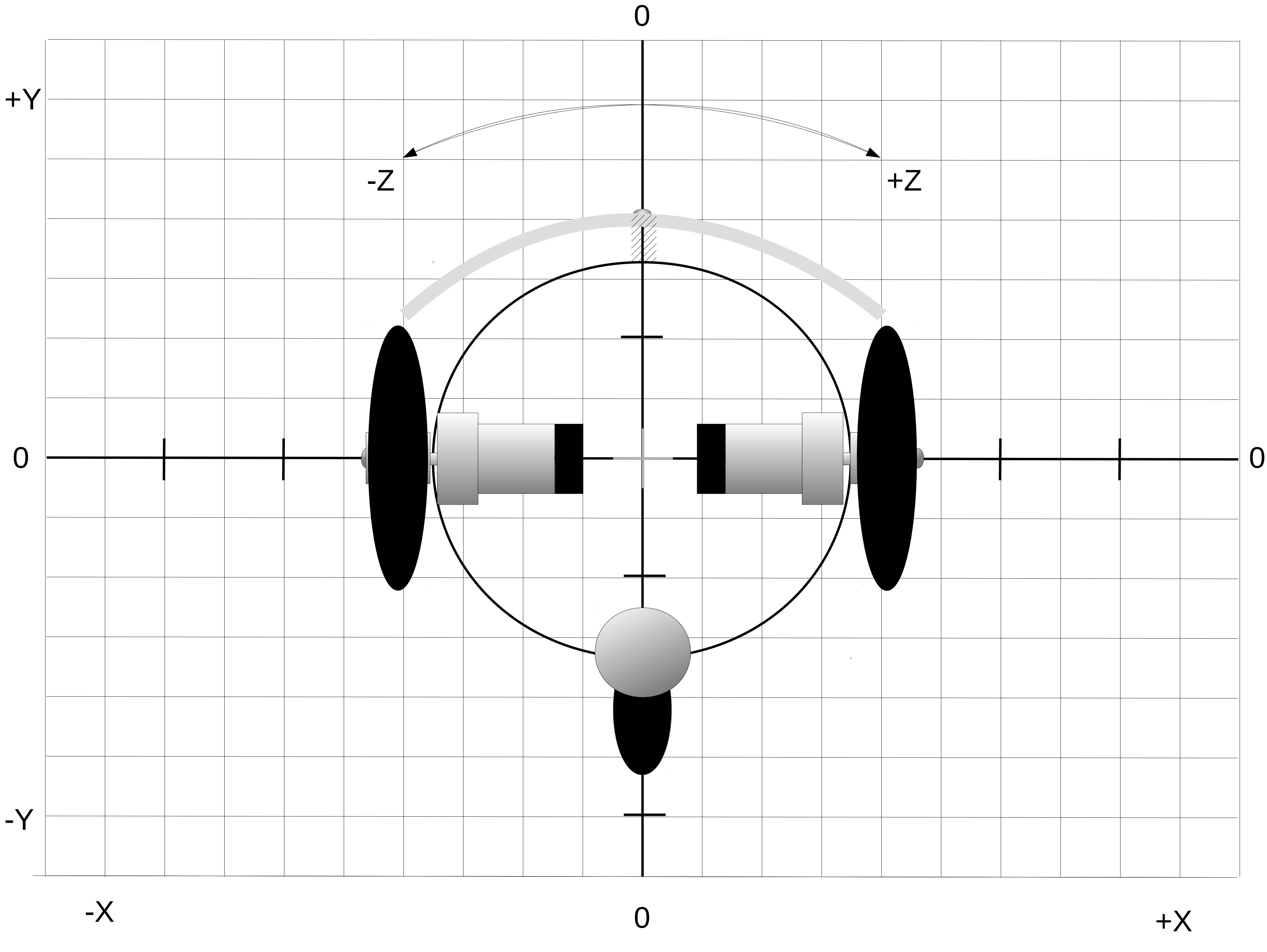
A. Determining Pose

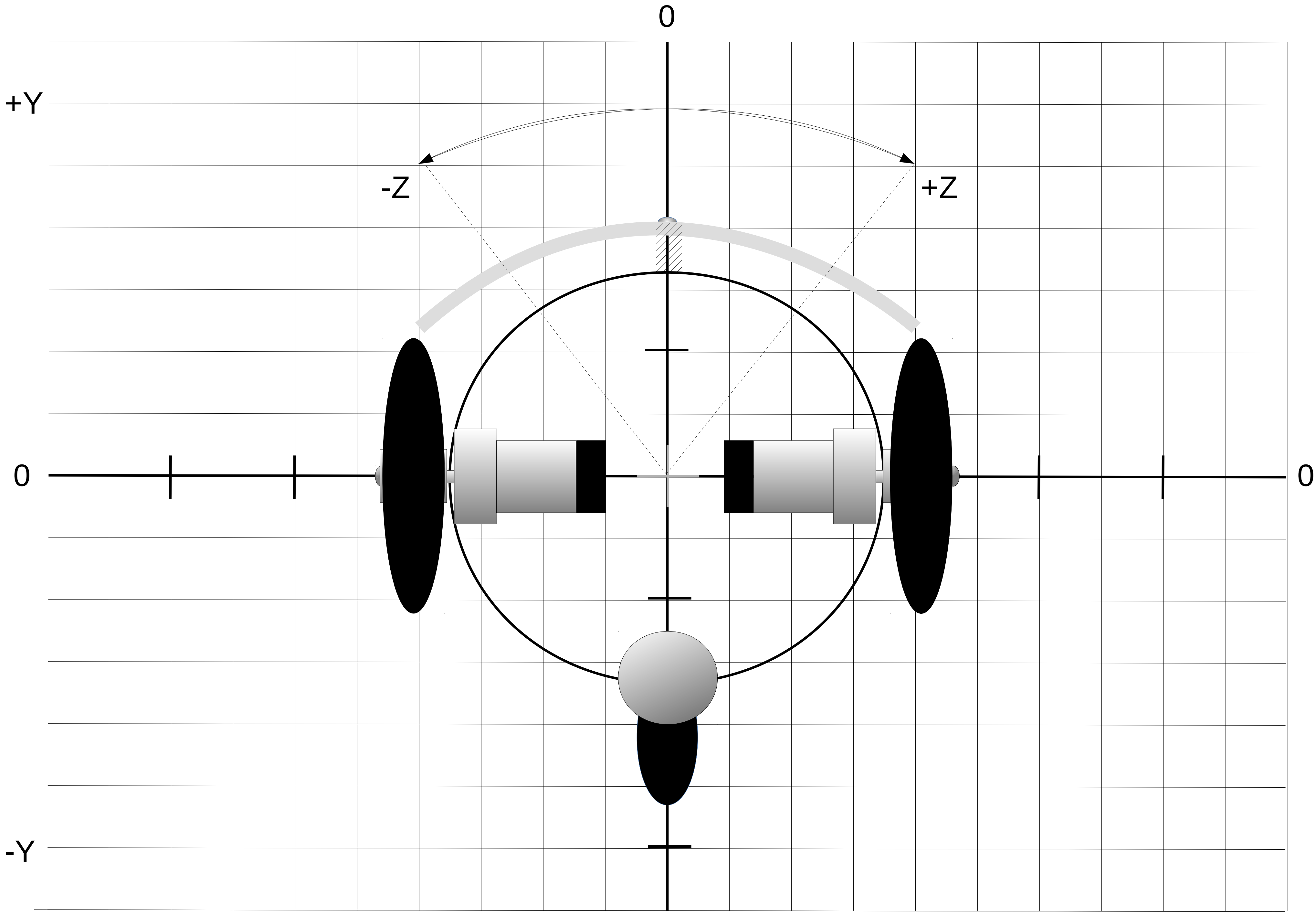
B. A Navigation Virtual Sensor

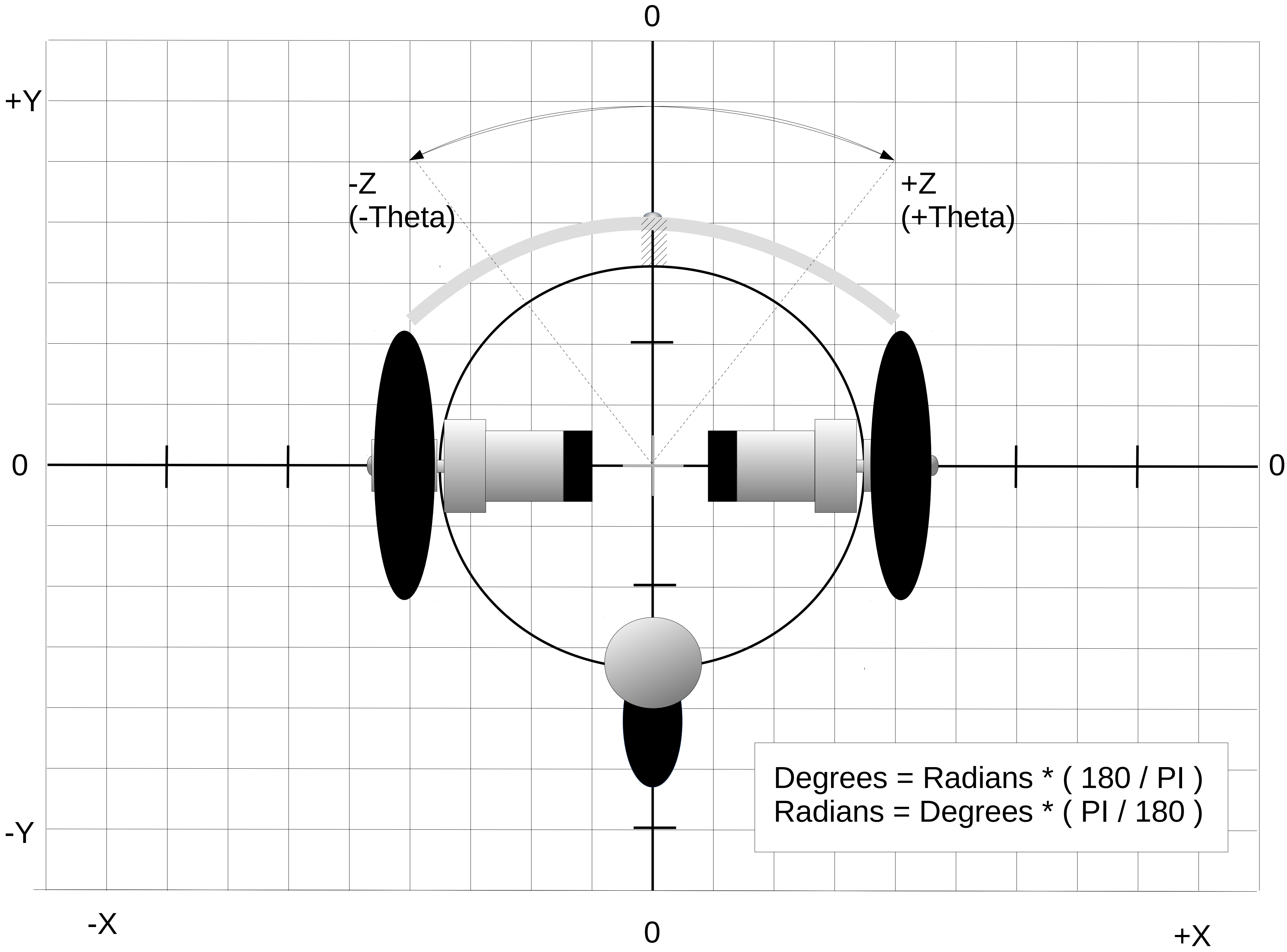
C. A Navigation Behavior

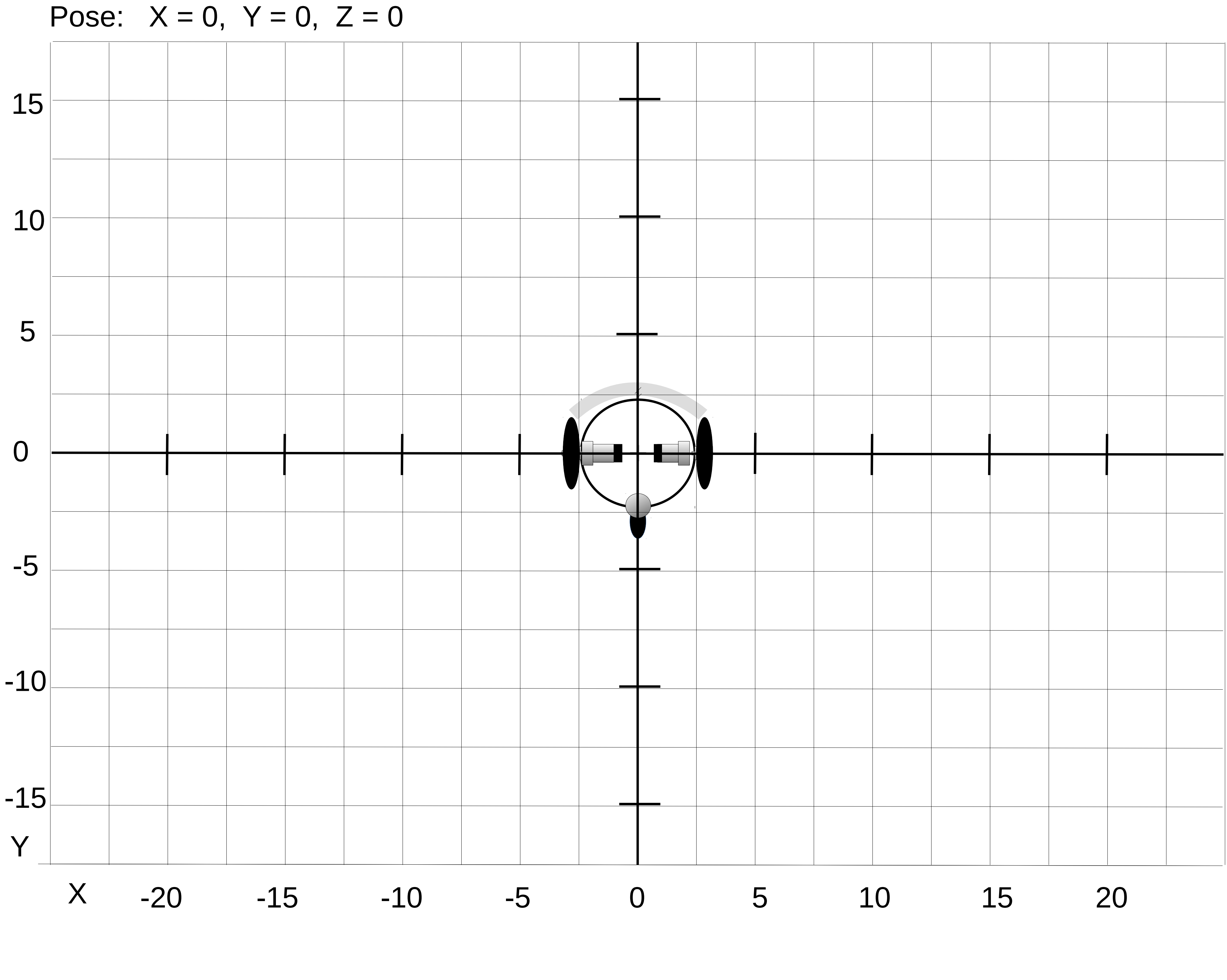
A. Determining POSE




0
+Y
-Z
+Z
0
0
-Y
-X
0
+X

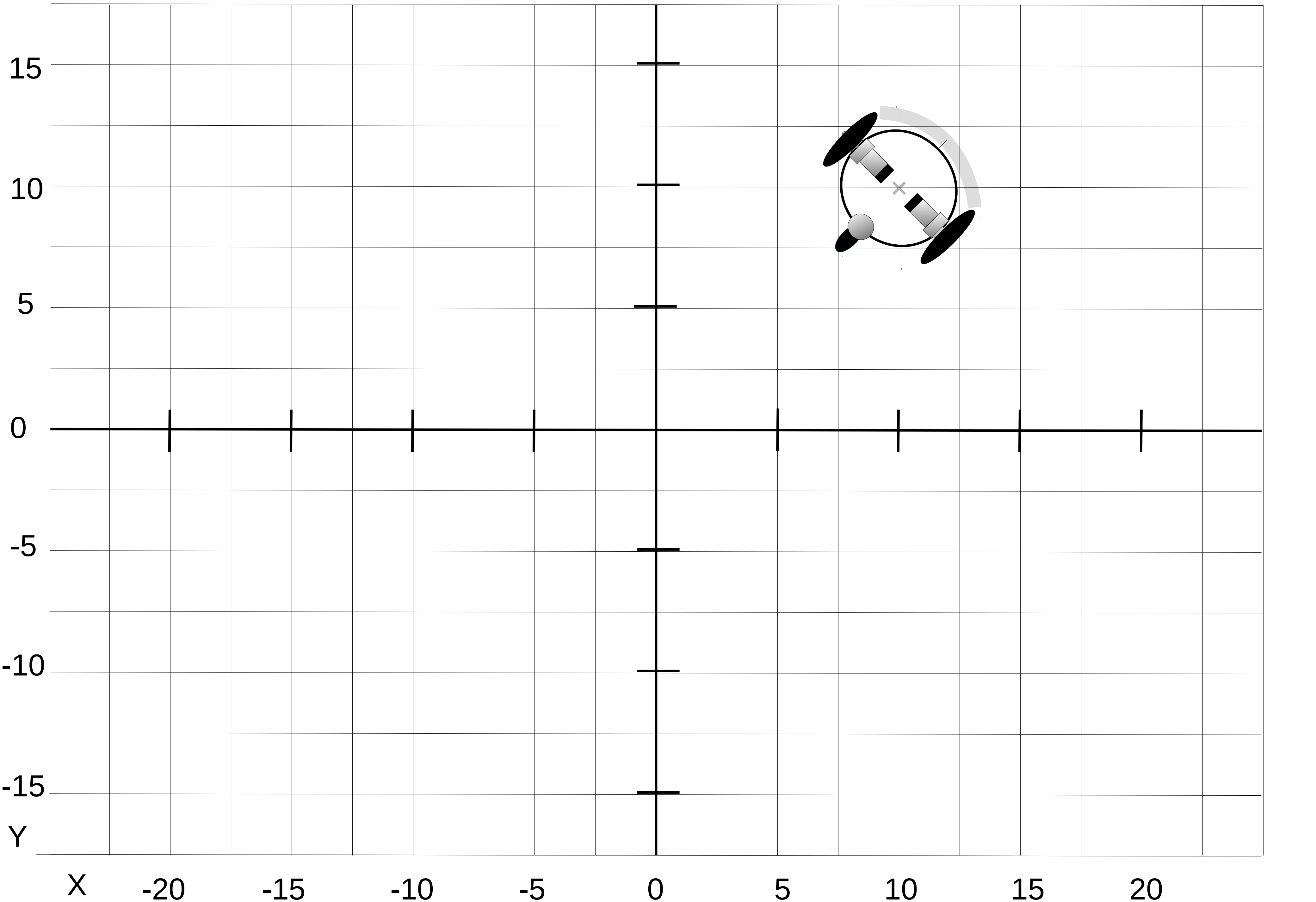

0
+Y
-Z
+Z
0
0
-Y
-X
0
+X


0
+Y
-Z
(-Theta)
+Z
(+Theta)
0
0
-Y
Degrees = Radians * (180 / PI)
Radians = Degrees * (PI / 180)
-X
0
+X

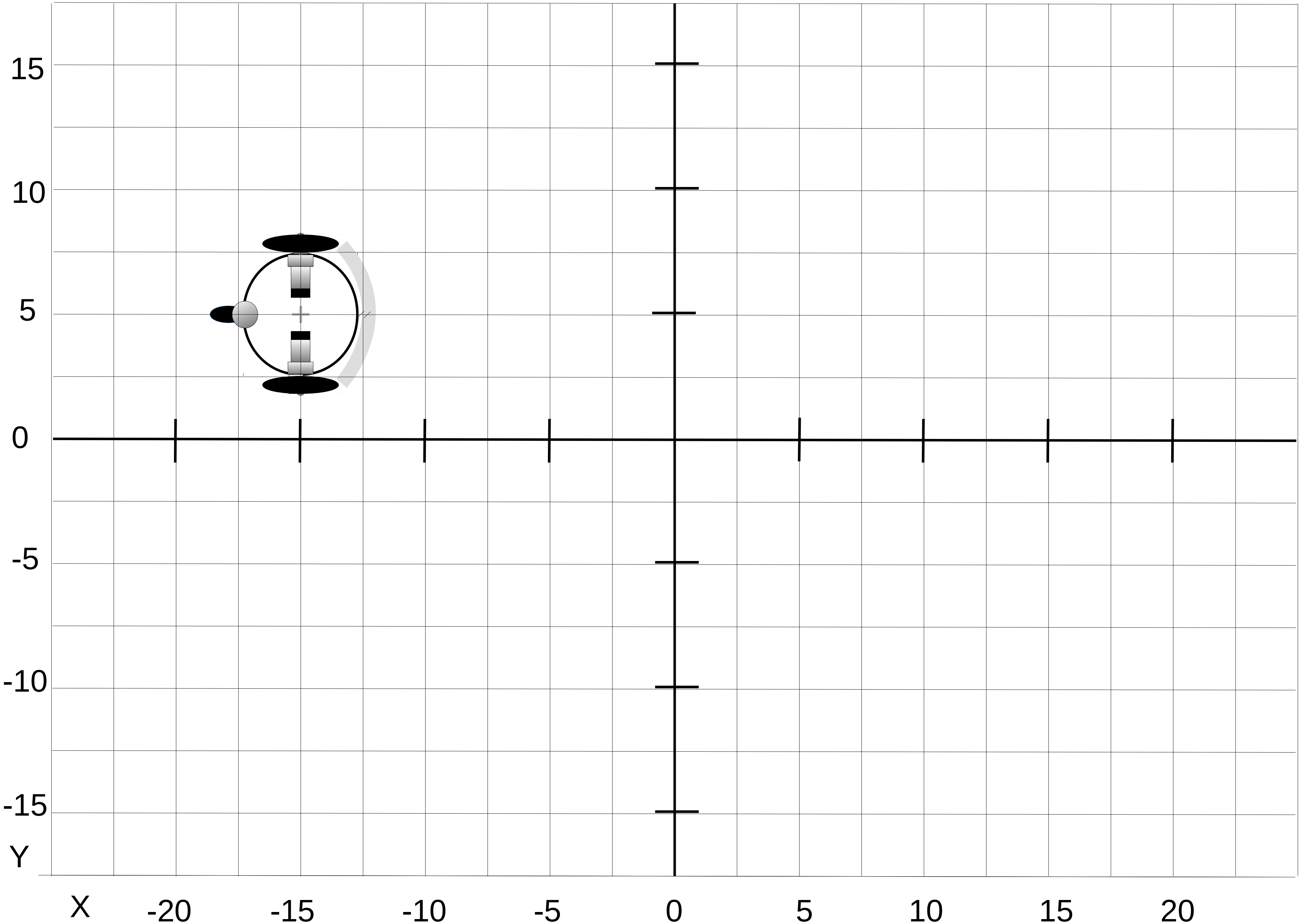


Pose: X = 0, Y = 0, Z = 0
15
10
5
0
-5
-10
-15
Y
X
-20
-15
-10
-5
0
5
10
15
20

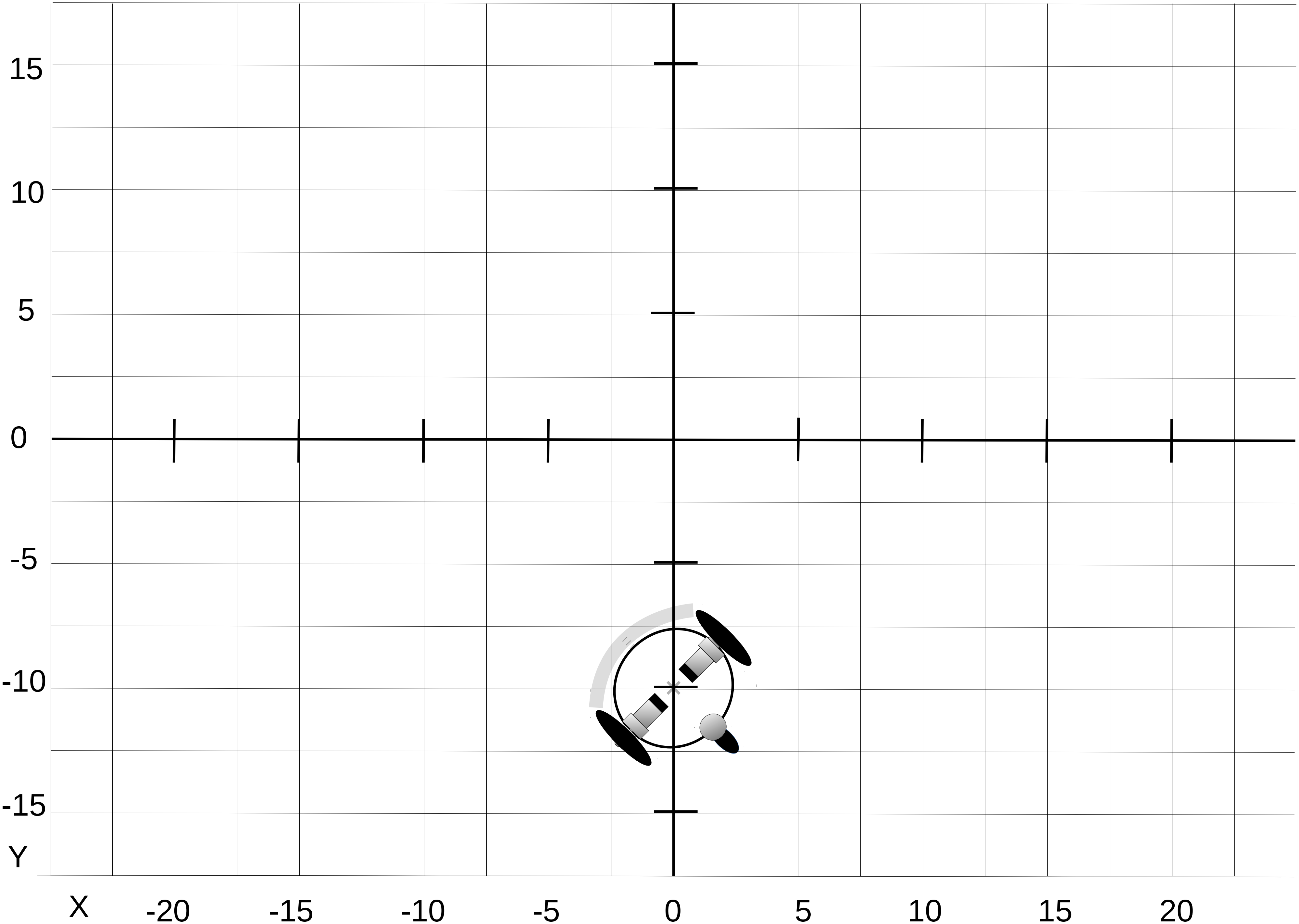
Pose: X = 10, Y = 10, Z = 45



Pose: X = -15, Y = 5, Z = 90



Pose: X = 0, Y = -10, Z = -45



Determining POSE:

```
float X_postion;          // x coordinate in inches
float Y_position;         // y coordinate in inches
float Theta;              // z coordinate in radians
```

Multiple methods exists for determining POSE: radio beacons, RTK GPS, RealSense T265 imu+depth sense camera, optical flow, and so forth.

The method of navigation described in this talk does not depend on how POSE is determined.   However, the robots in these demonstrations and videos all use some form of wheel odometry to determine POSE.

Fun Facts to Know and Tell:

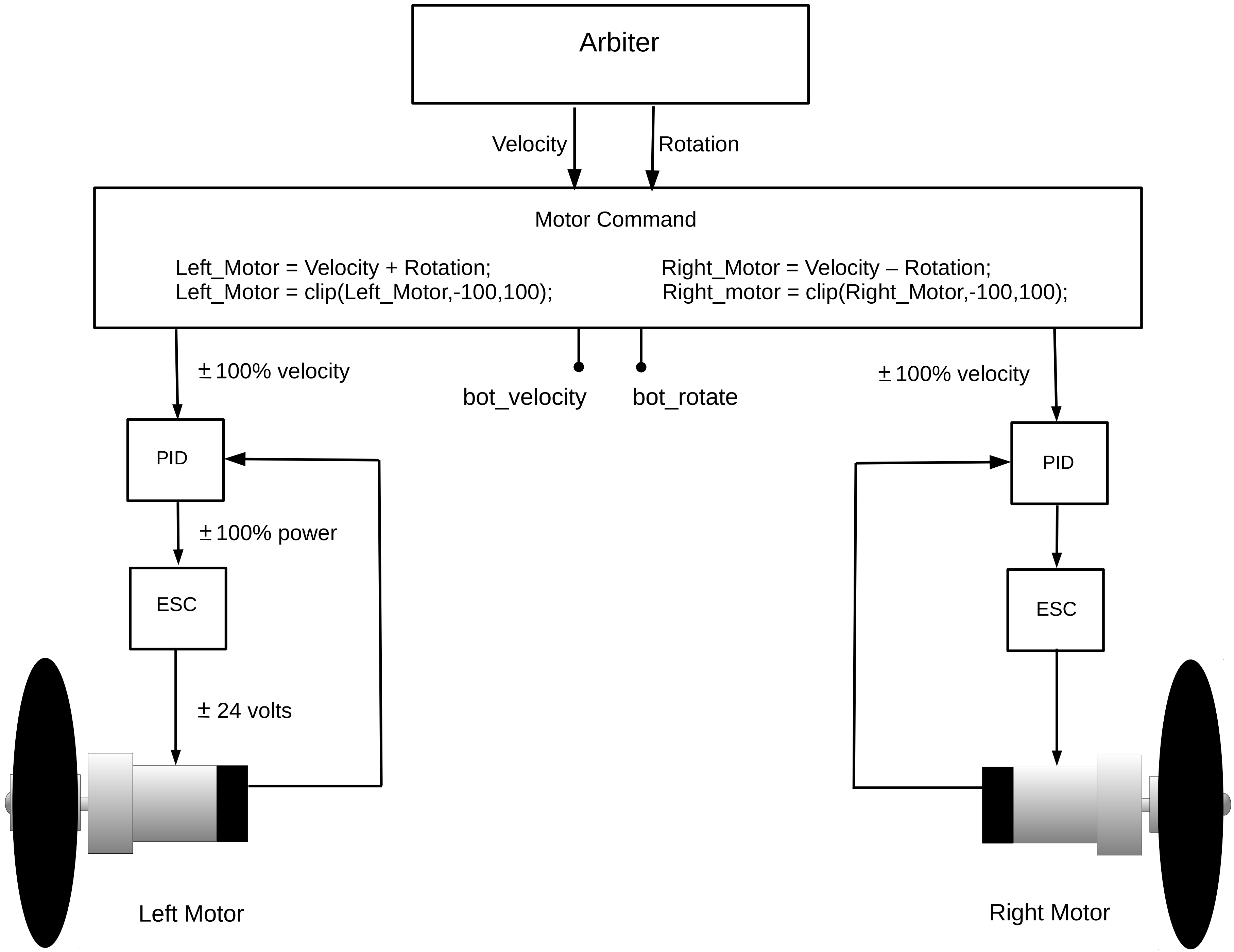
Odometry: Greek hodometron, from hodos way, road + metron measure.
Archimedes' hodometron was used by Romans to layout mile markers.

Three forms of odometry used on my robots:

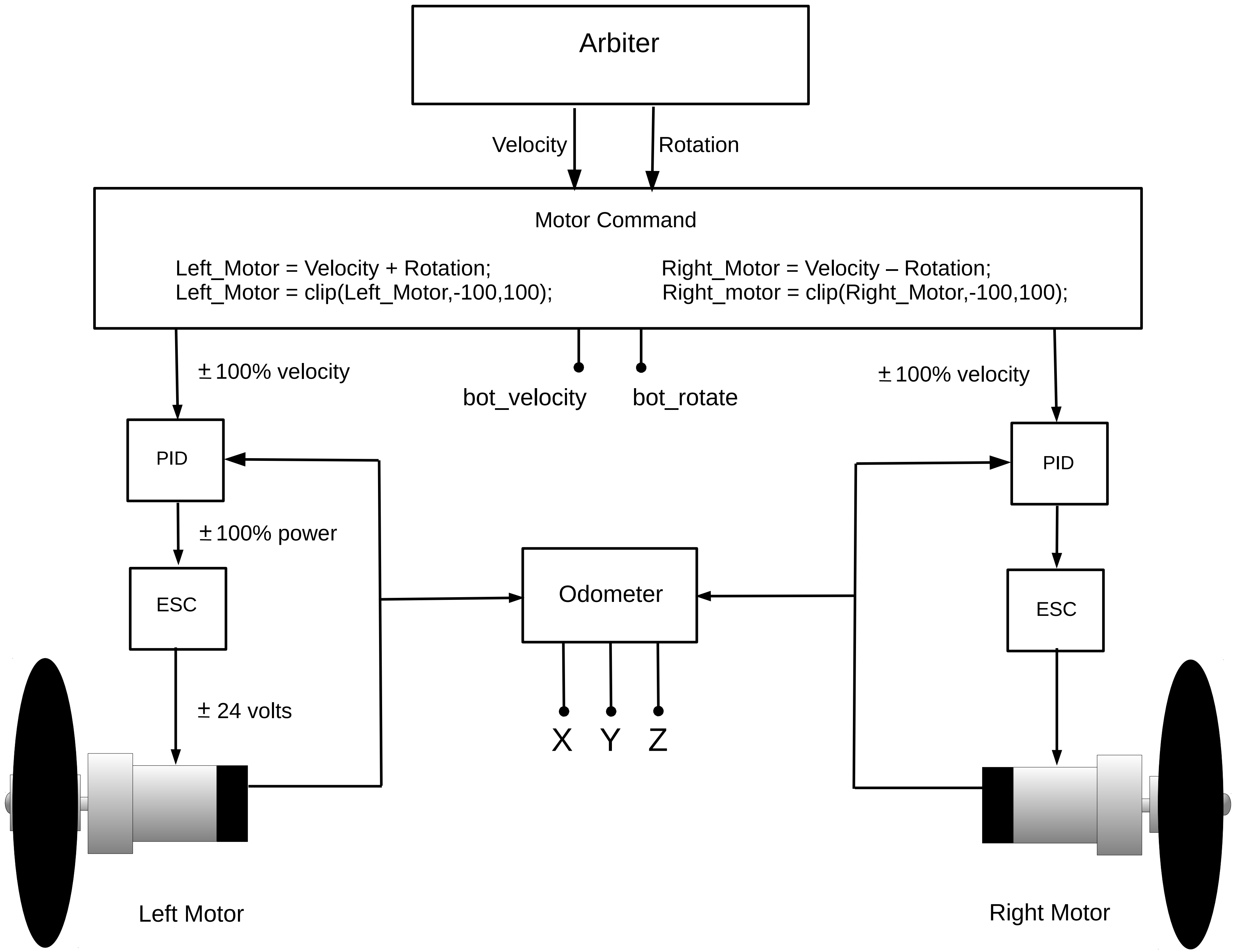
1. Wheel Odometry (nBot, LegoBot)

2. Wheel Odometry + Gyro (Rcat)

3. Wheel Odometry + IMU   (jBot)



Arbiter
Velocity
Rotation
Motor Command
Left_Motor = Velocity + Rotation;
Left_Motor = clip(Left_Motor,-100,100);
Right_Motor = Velocity – Rotation;
Right_motor = clip(Right_Motor,-100,100);
± 100% velocity
bot_velocity
bot_rotate
± 100% velocity
PID
PID
± 100% power
ESC
ESC
± 24 volts
Left Motor
Right Motor


Arbiter
Velocity
Rotation
Motor Command
Left_Motor = Velocity + Rotation;
Left_Motor = clip(Left_Motor,-100,100);
Right_Motor = Velocity – Rotation;
Right_motor = clip(Right_Motor,-100,100);
± 100% velocity
bot_velocity
bot_rotate
± 100% velocity
PID
PID
± 100% power
ESC
Odometer
ESC
± 24 volts
X Y Z
Left Motor
Right Motor

Determing POSE

1. Wheel Odometry

```
float X_position;          // persistent variable X in inches
float Y_position;          // persistent variable Y in inches
float Theta;               // persistent variable Z in radians

void odometer ( void )
{
    left_inches = read_left_encoder() / LEFT_CLICKS_PER_INCH;
    right_inches = read_right_encoder() / RIGHT_CLICKS_PER_INCH;

    inches = ( left_inches + right_inches ) / 2.0;
    wheel_rate = ( left_inches – right_inches ) / WHEEL_BASE;

    Theta += wheel_rate;
    Theta -= (float) ( (int) ( Theta / TWOPI ) ) * TWOPI;     // clip to +- 360

    X_position += inches * sin ( Theta );
    Y_position += inches * cos ( Theta );
}
```

Determining POSE

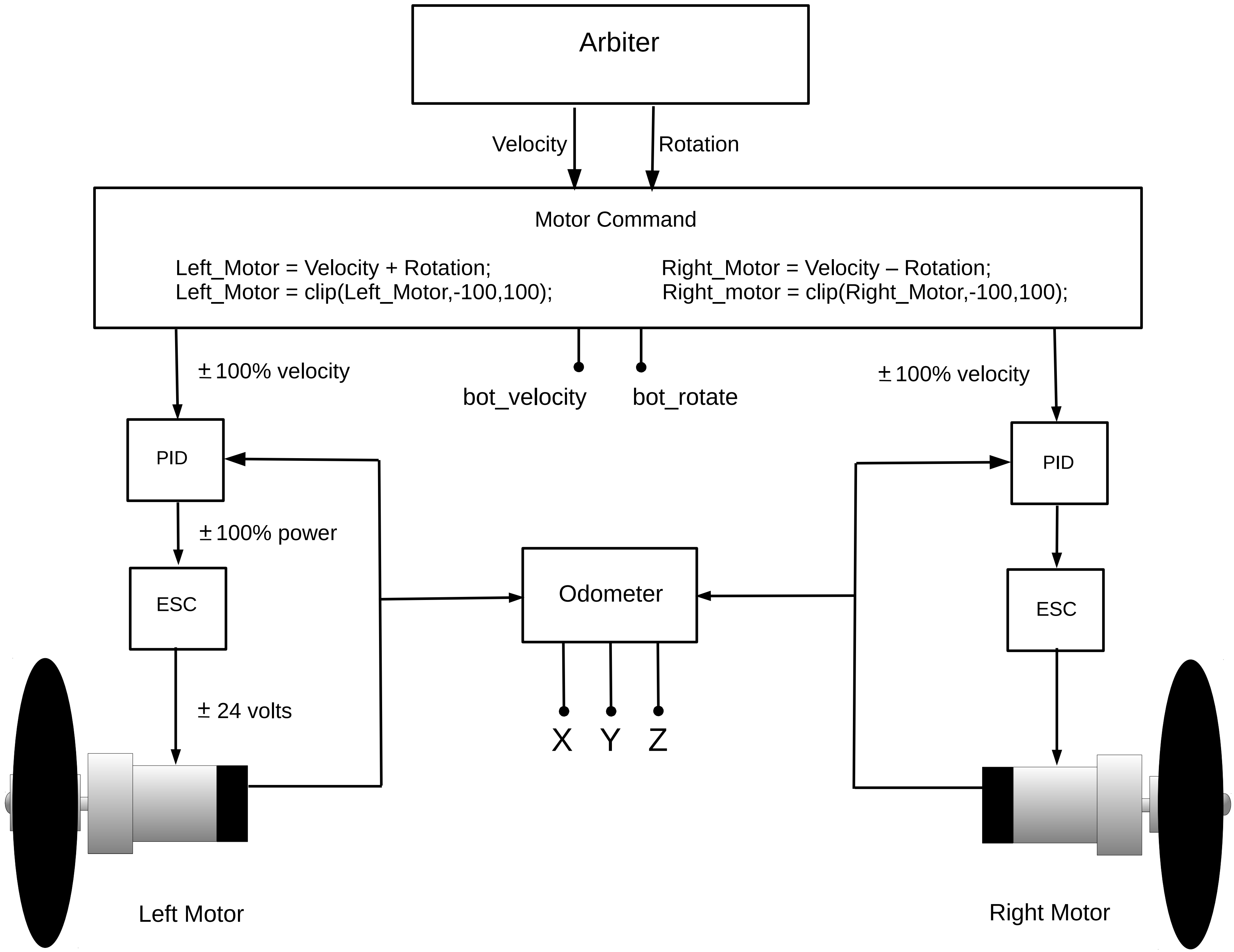
2. Wheel Odometry + Rate Gyro

```
void odometer ( void )
{
    left_inches = read_left_encoder() / LEFT_CLICKS_PER_INCH;
    right_inches = read_right_encoder() / RIGHT_CLICKS_PER_INCH;

    inches = ( left_inches + right_inches ) / 2.0;
    wheel_rate = ( left_inches – right_inches ) / WHEEL_BASE;

    gyro_rate = read_rate_gyro();
    gyro_rate = ( gyro_rate * ( PI / 180 ) ) / 25;

    if (p_gyro_enable)
        Theta += gyro_rate;
    else
        Theta += wheel_rate;

    Theta -= (float) ( (int) ( Theta / TWOPI ) ) * TWOPI;

    X_position += inches * sin ( Theta );
    Y_position += inches * cos ( Theta );
}
```

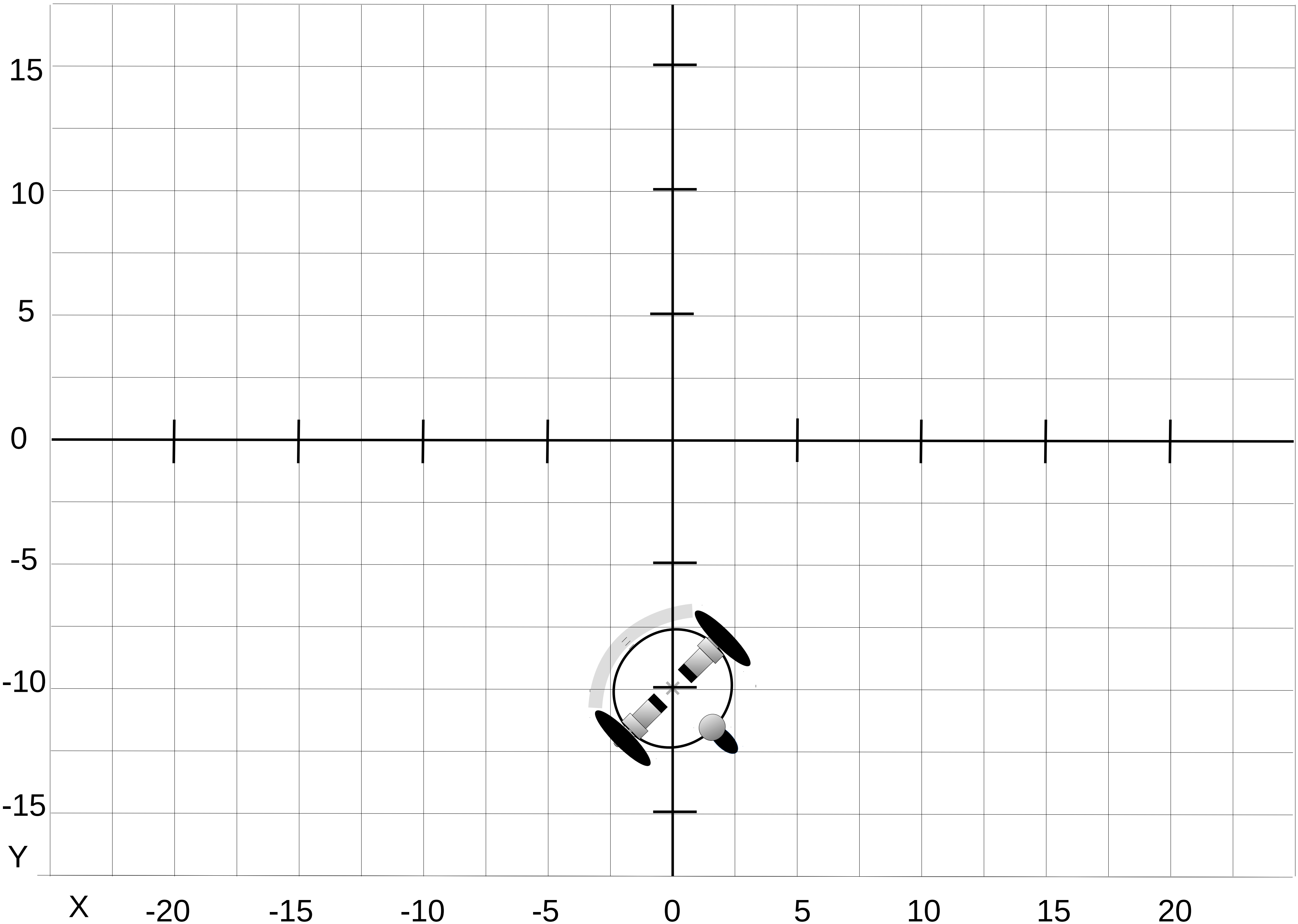
Determining POSE

3. Wheel Odometry + IMU (Euler angles)

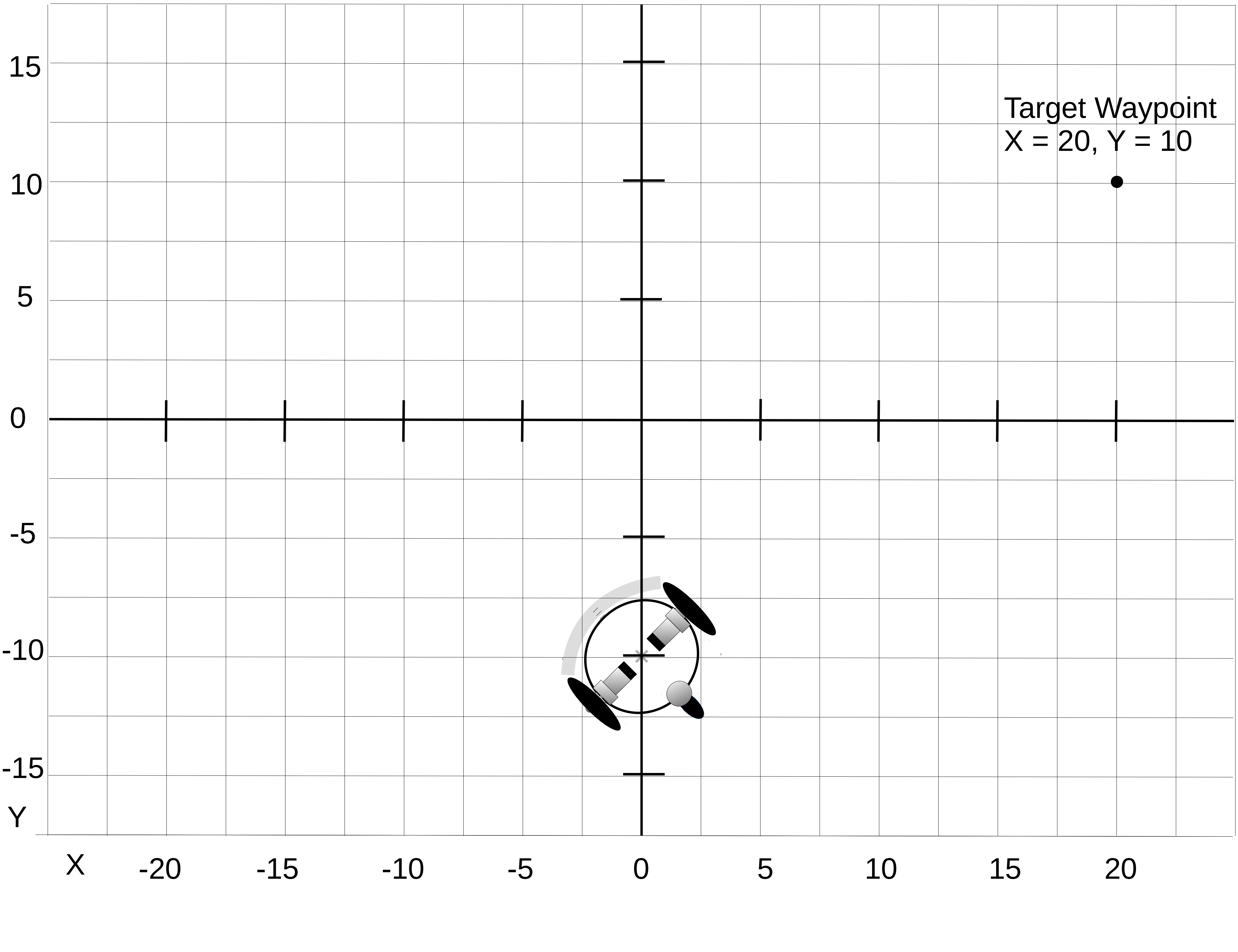
```
void odometer ( void )
{
       left_inches = read_left_encoder() / LEFT_CLICKS_PER_INCH;
       right_inches = read_right_encoder() / RIGHT_CLICKS_PER_INCH;

       inches = ( left_inches + right_inches ) / 2.0;
       wheel_rate = ( left_inches – right_inches ) / WHEEL_BASE;

       if (p_imu_enable) Theta = ( imu.yaw * ( PI / 180 ) ) + north_offset;
       else {
              Theta += wheel_rate;
              Theta -= (float) ( (int) ( Theta / TWOPI ) ) * TWOPI;
       }

       X_position += inches * sin ( Theta );
       Y_position += inches * cos ( Theta );
}
```

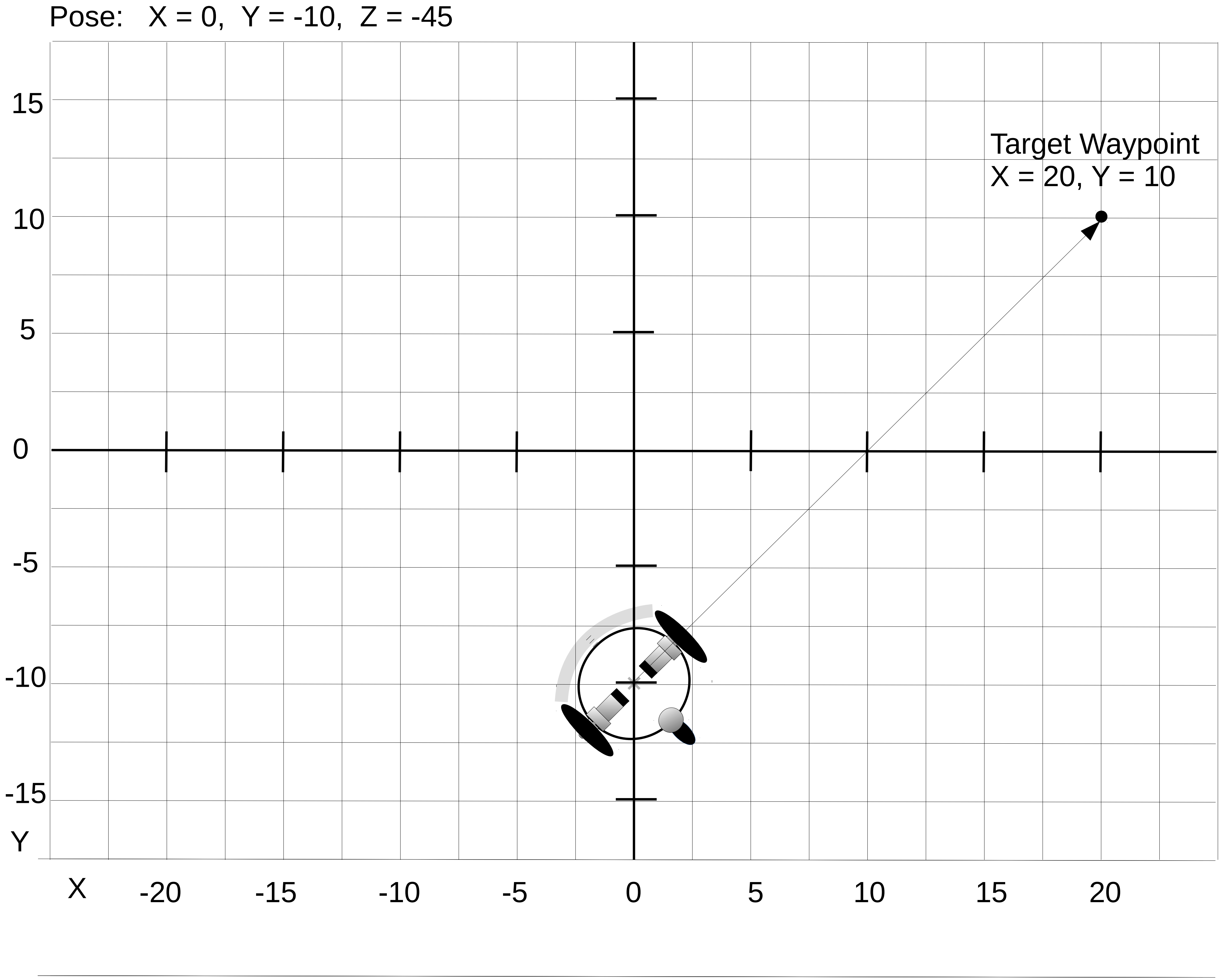

Arbiter
Velocity
Rotation
Motor Command
Left_Motor = Velocity + Rotation;
Left_Motor = clip(Left_Motor,-100,100);
Right_Motor = Velocity – Rotation;
Right_motor = clip(Right_Motor,-100,100);
± 100% velocity
bot_velocity
bot_rotate
± 100% velocity
PID
PID
± 100% power
ESC
Odometer
ESC
± 24 volts
X Y Z
Left Motor
Right Motor

Pose: X = 0, Y = -10, Z = -45

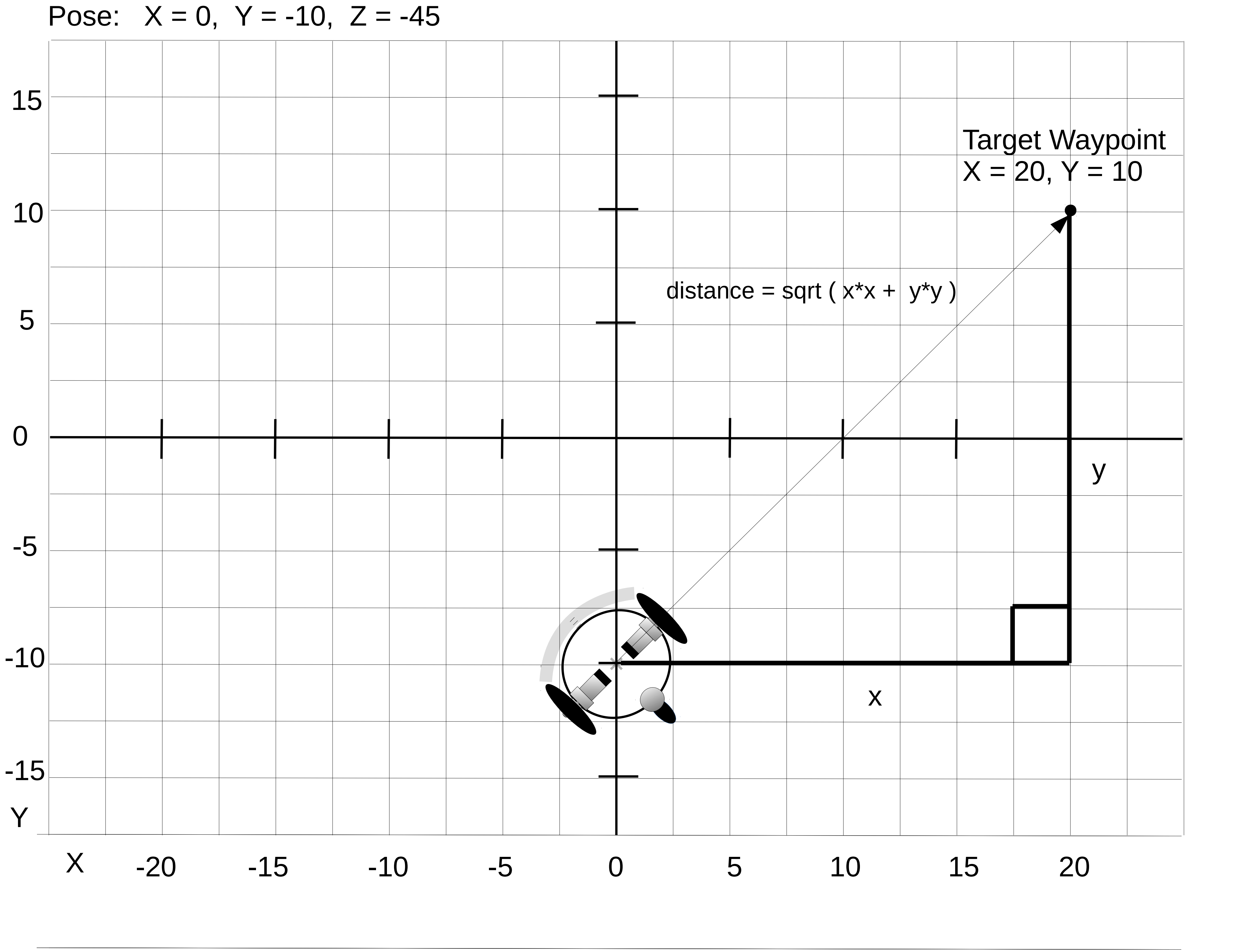


Where we want to go: Waypoints

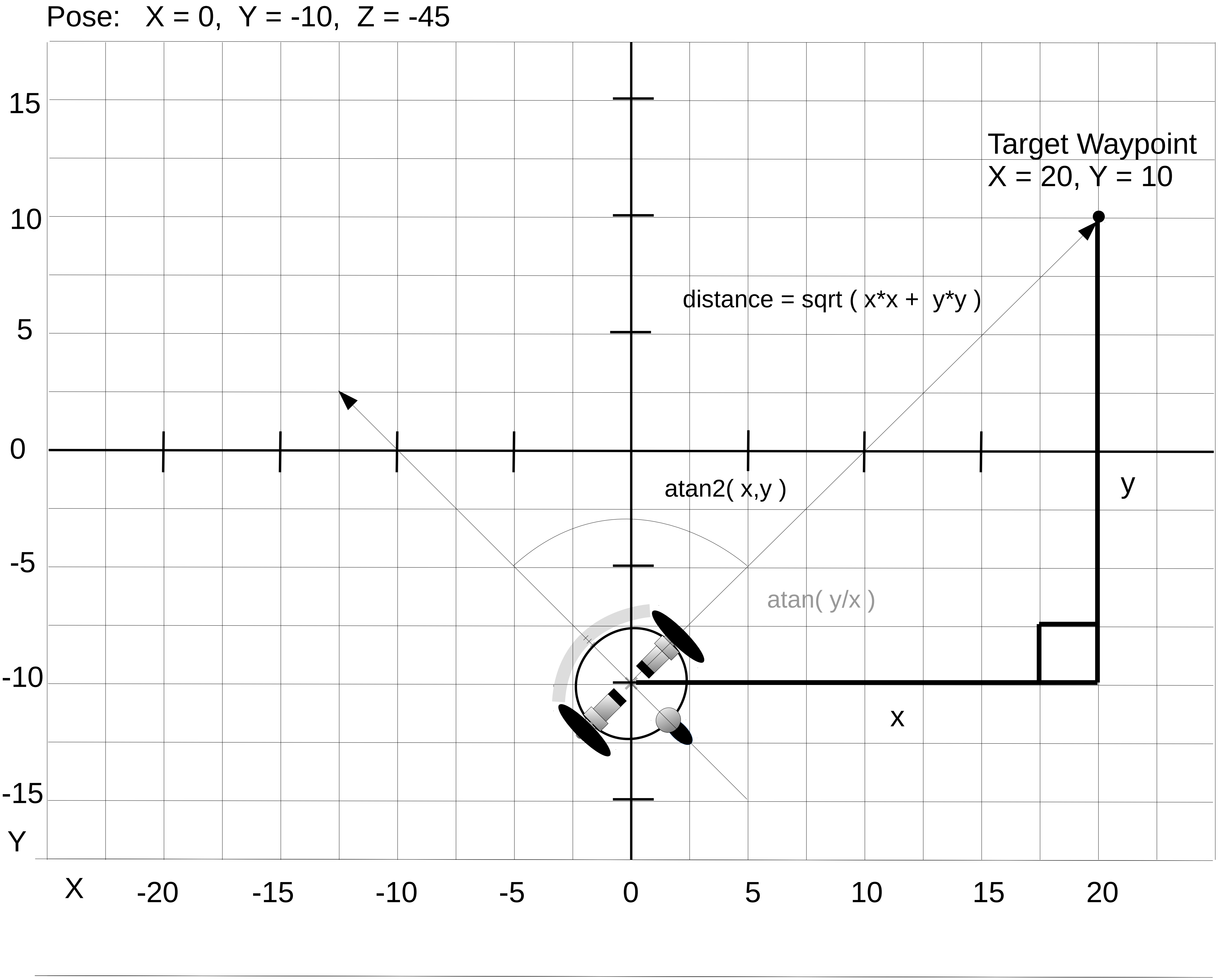




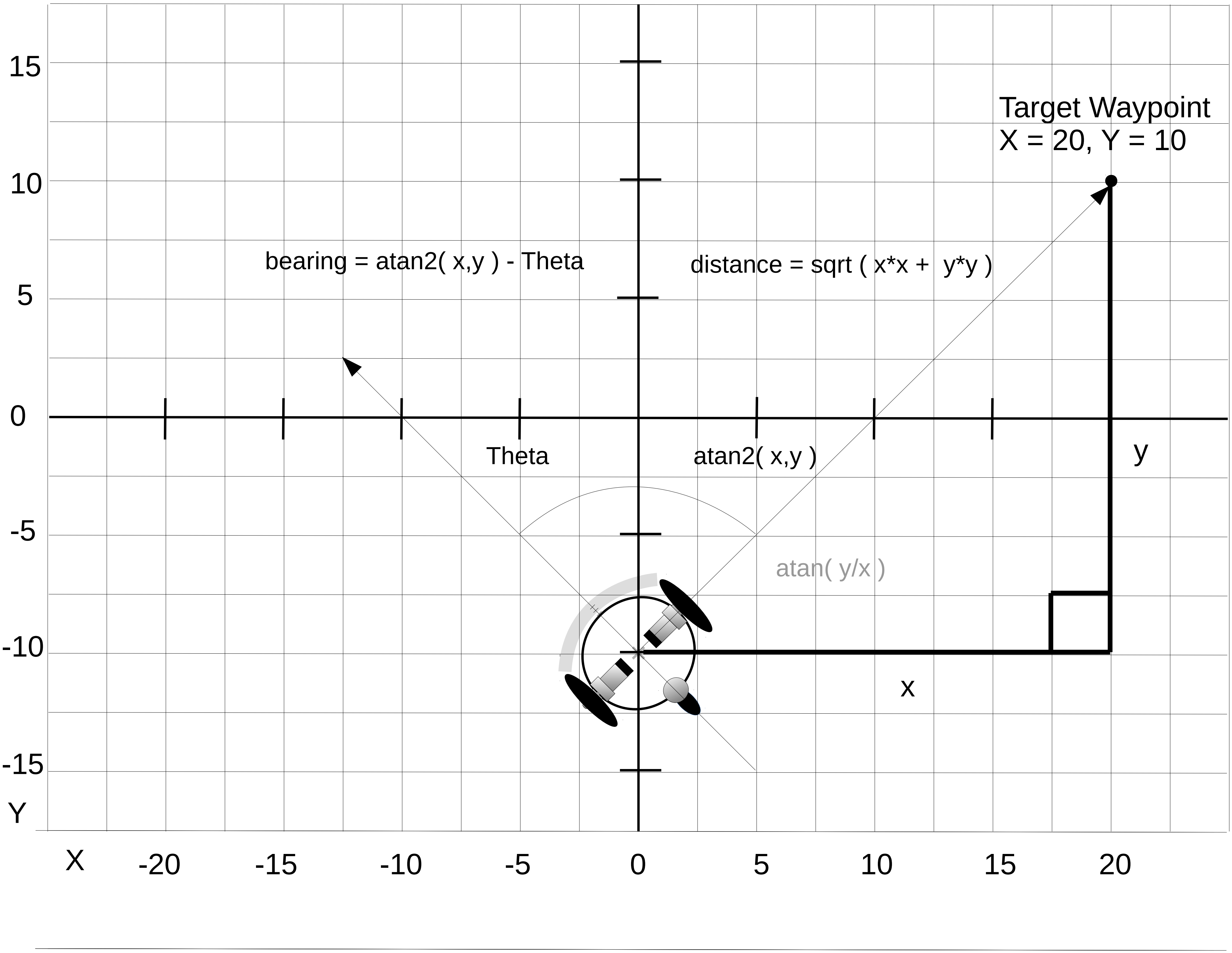
Pose: X = 0, Y = -10, Z = -45
Target Waypoint
X = 20, Y = 10
15
10
5
0
-5
-10
-15
Y
X
-20
-15
-10
-5
0
5
10
15
20



Pose: X = 0, Y = -10, Z = -45
Target Waypoint
X = 20, Y = 10
distance = sqrt (x*x + y*y)
y
x
15
10
5
0
-5
-10
-15
Y
X
-20
-15
-10
-5
0
5
10
15
20


Pose: X = 0, Y = -10, Z = -45
Target Waypoint
X = 20, Y = 10
distance = sqrt (x*x + y*y)
atan2(x,y)
atan(y/x)
x
y
15
10
5
0
-5
-10
-15
Y
X
-20
-15
-10
-5
0
5
10
15
20

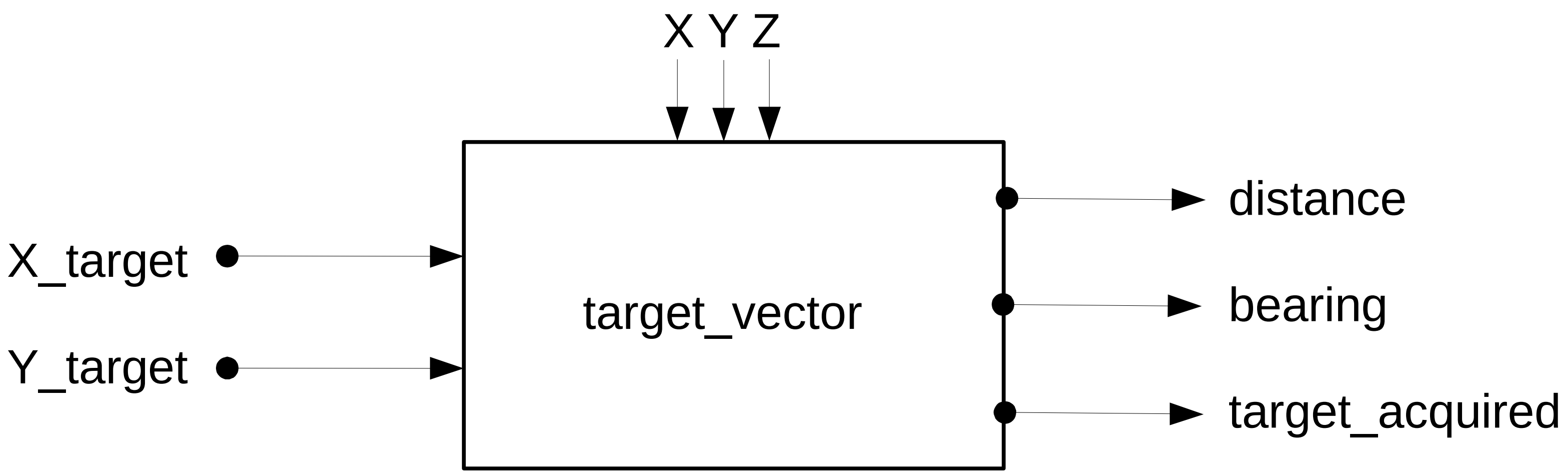
Pose: X = 0, Y = -10, Z = -45



B. A Navigation Virtual Sensor: target_vector()

POSE/Odometry provides at 25 Hz:

```
float X_postion;          // x coordinate in inches
float Y_position;         // y coordinate in inches
float Theta;              // z coordinate in radians
```



Virtual Sensors

POSE/Odometry provides:

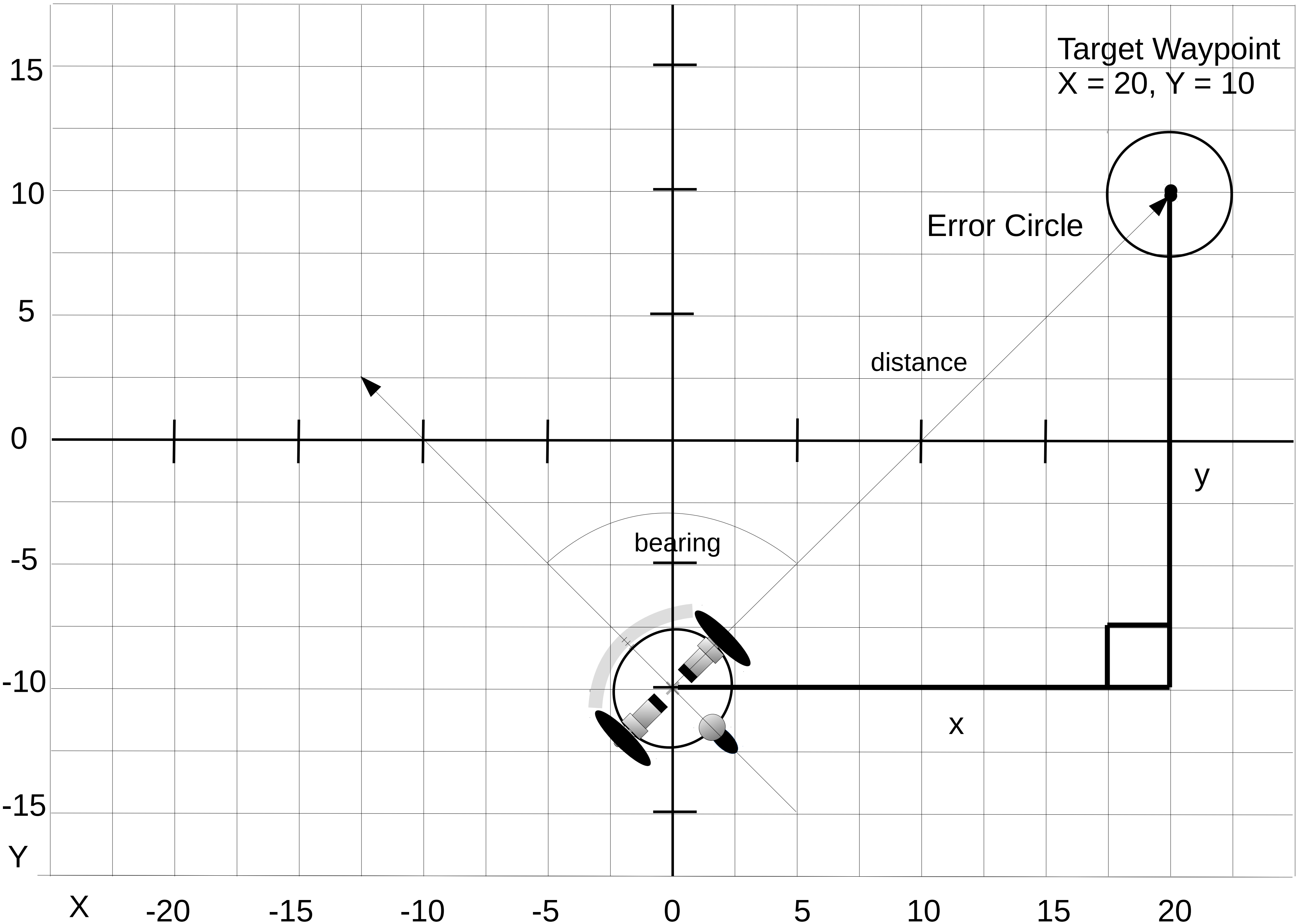
```
float X_postion;        // x coordinate in inches
float Y_position;       // y coordinate in inches
float Theta;            // z coordinate in radians
```

```
int target_vector ( float X_target, Y_target, *distance, *bearing )
{
    float x, y;

    x = X_target – X_position;
    y = Y_target – Y_position;

    *distance = sqrt ( ( x*x ) + ( y*y ) );
    *bearing = atan2 ( x, y ) - Theta;

    return target_acquired ( *distance );
}
```

```
int target_acquired ( float distance )
{
	if ( distance == 0 ) return TRUE;
	else return FALSE;
}
```

```
int target_acquired ( float distance )
{
        if ( distance <  ERR_CIRCLE ) return TRUE;
        else return FALSE;
}
```

Pose: X = 0, Y = -10, Z = -45



```
int target_acquired ( float distance, last_distance )
{
	if ((distance <  ERR_CIRCLE)  &&
		(distance > last_distance))
			return TRUE;
	else return FALSE;
}
```

Virtual Sensor

POSE/ODOMETRY provides:

```
float X_postion;        // x coordinate in inches
float Y_position;       // y coordinate in inches
float Theta;            // z coordinate in radians
```

```
int target_vector ( float X_target, Y_target, *distance, *bearing )
{
    float x, y;
    float last_distance = *distance;

    x = X_target – X_position;
    y = Y_target – Y_position;

    *distance = sqrt ( ( x*x ) + ( y*y ) );
    *bearing = atan2 ( x, y ) - Theta;

    return target_acquired ( *distance, last_distance );
}
```

C. Navigation behavior

Read Virtual Sensor:

call target_vector () and get current distance and bearing to target

Steering:

If bearing is positive, turn right.

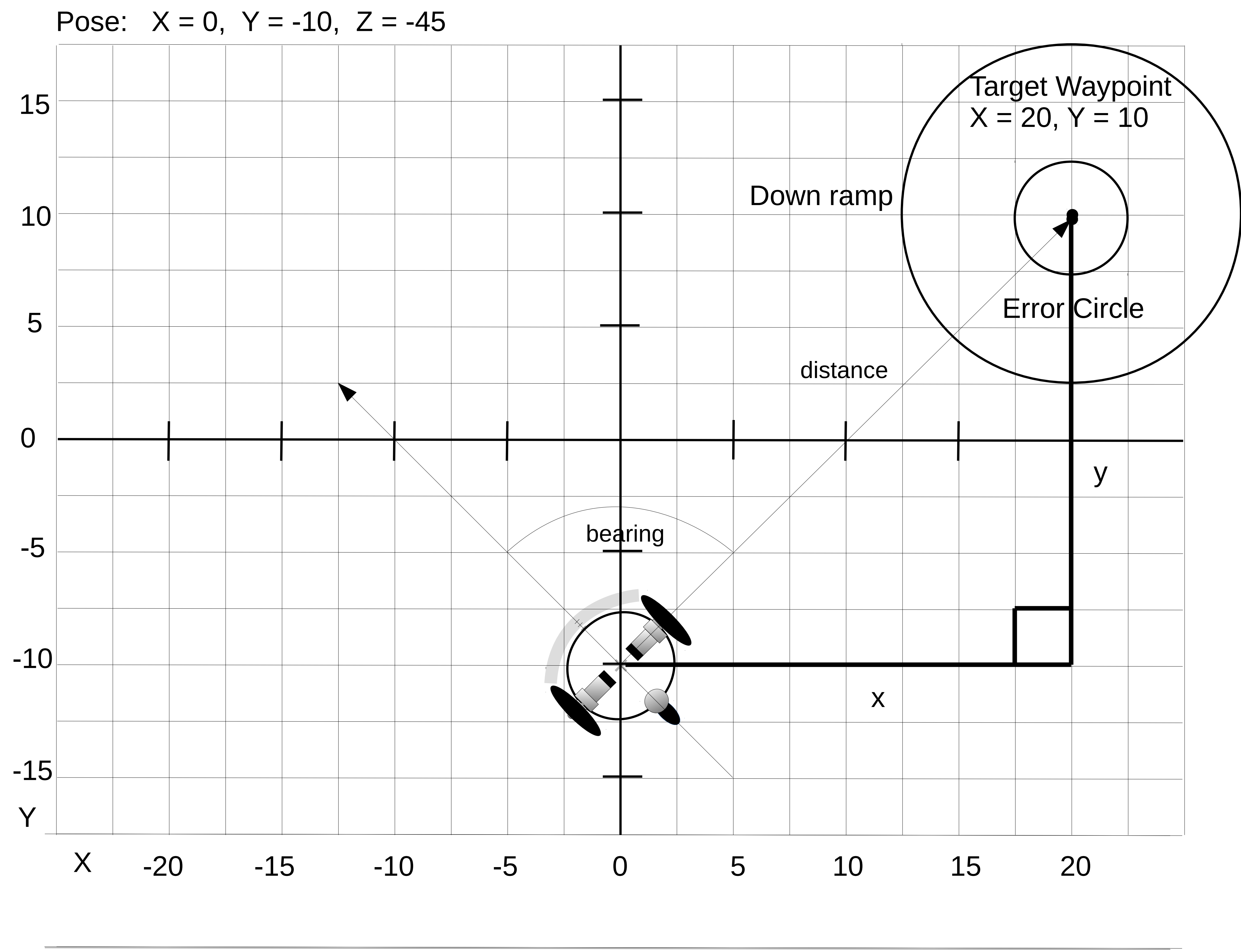
If bearing is negative turn left.

if bearing is in DEADZONE, go straight.

Speed:

if (distance > DOWNRAMP) velocity = p_user_velocity.

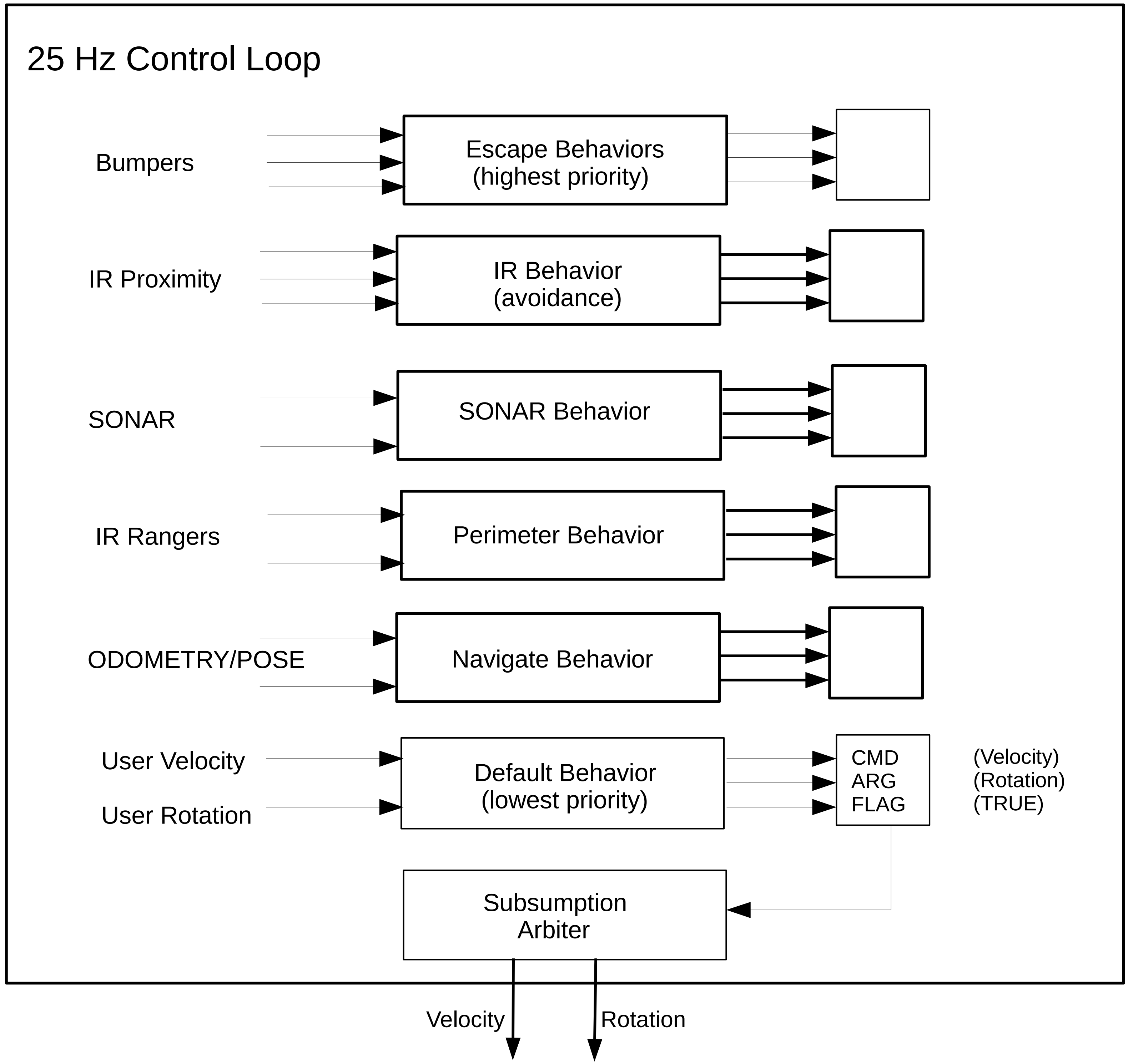
// else slow down approaching waypoint:
else velocity = p_user_velocity * (distance / DOWNRAMP)



Pose: X = 0, Y = -10, Z = -45
Target Waypoint
X = 20, Y = 10
Down ramp
Error Circle
distance
bearing
y
x
15
10
5
0
-5
-10
-15
Y
X
-20
-15
-10
-5
0
5
10
15
20

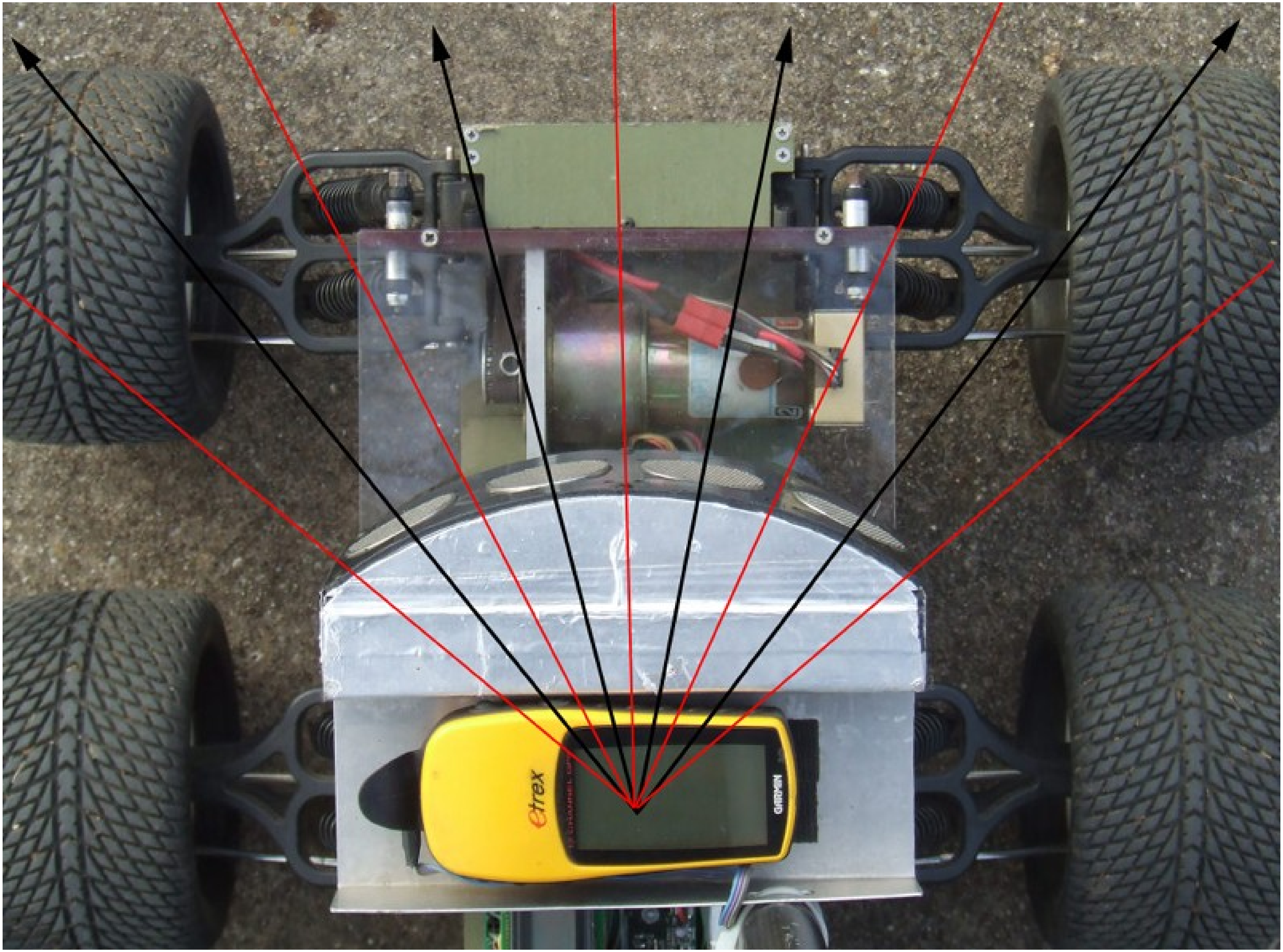
```
CMDBLOCK navigate;              // output struct
float distance, bearing;        // persistent variables

int navigate_target ( float X_target, Y_target )
{
        if  ( target_vector ( X_target, Y_target, &distance, &bearing ))   {        // arrived?
                return TRUE;                                                        // exit true
        }
        if ( ( bearing < DEADZONE ) && ( bearing > -DEADZONE ) )  {                 // in deadzone?
                        navigate.arg = slew_rot( 0, p_nav_rrate );                  // go straight
        } else          {

                if (bearing > DEADZONE) {                                           // above DZ?
                        navigate.arg = slew_rot (  p_nav_turn, p_nav_rrate );       // turn right
                }
                if ( bearing < -DEADZONE ) {                                        // below DZ?
                        navigate.arg = slew_rot ( -p_nav_turn, p_nav_rrate );       // turn left
                }
        }
                                                                                    // SPEED
        if ( ( distance < DOWNRAMP )  &&  ( p_stop_enable ) ) {                     // inside DR?

                navigate.cmd = p_user_velocity * ( distance / DOWNRAMP );           // slow down
                navigate.cmd = clip ( navigate.cmd, MINSPEED, 100 );

        }  else         {                                                           // else
                navigate.cmd = slew_vel ( p_user_velocity, p_nav_vrate );           // full speed
        }

        return FALSE;           // exit false, not there yet
}
```

```
void navigate_behavior ( void )
{
        extern NAVLIST *navlist, *navlist_begin, *navlist_end;        // X,Y list

        float dist, bear;

        if ( navlist ) {

                navigate.flag = TRUE;

                if ( ( navigate_target ( navlist->X, navlist->Y ) ) == TRUE )  {

                        navlist++;
                        if ( navlist > navlist_end )  {
                                if ( p_nav_repeat )  navlist = navlist_begin;
                                else  navlist = 0;
                        }

                        if (  ( navlist ) && ( p_stop_enable ) )   {        // stopped?
                                target_vector ( navlist->X, navlist->Y, &dist, &bear);
                                rotate ( bear );
                        }
                }
        } else       {
                navigate.flag = FALSE;
        }
}
```


25 Hz Control Loop
Bumpers
Escape Behaviors
(highest priority)
IR Proximity
IR Behavior
(avoidance)
SONAR
SONAR Behavior
IR Rangers
Perimeter Behavior
ODOMETRY/POSE
Navigate Behavior
User Velocity
User Rotation
Default Behavior
(lowest priority)
CMD
ARG
FLAG
(Velocity)
(Rotation)
(TRUE)
Subsumption
Arbiter
Velocity
Rotation

Demo 5

Live
RCAT: navigation and obstacle avoidance


etrex
GARMIN

Demo 6

Video

jBot: Hat trick

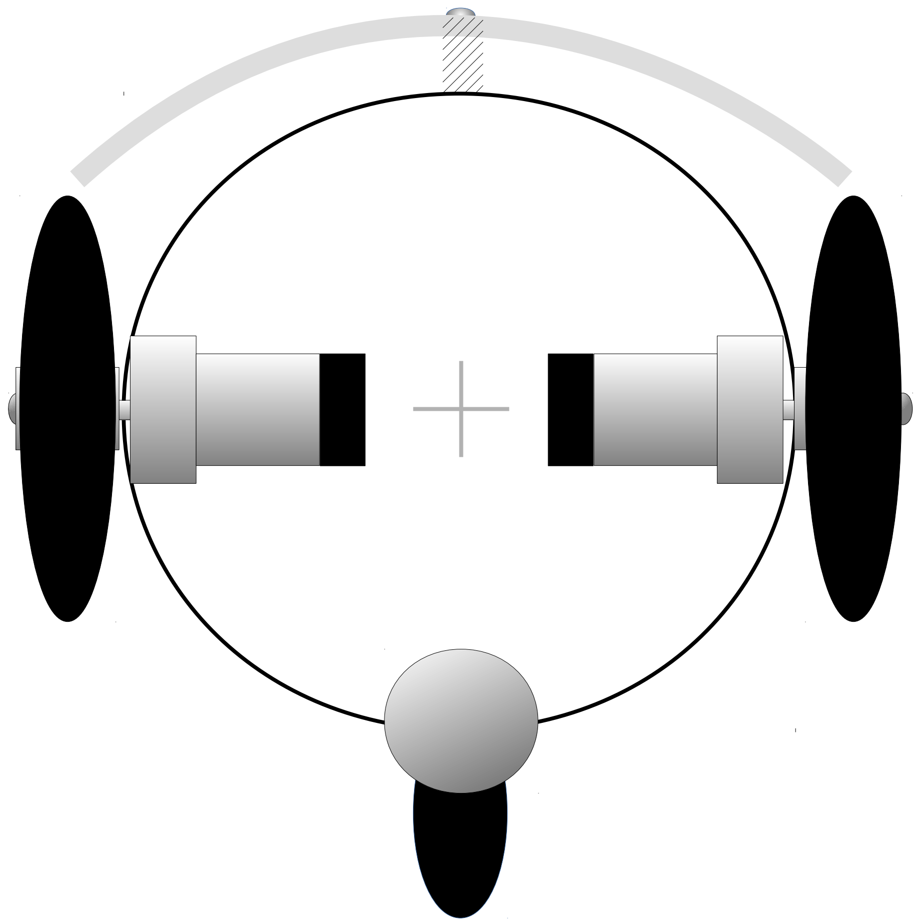
Jbot's Control Loop

```
void sensors (ASIZE ignored)
{
	TSIZE t;

	t = sysclock;
	while (1) {

		/* utilities */
		do_speedometer();
		odometers();

		/* behaviors */
		prowl_task();
		bump_task();
		deadman_task();
		navigate_task();
		escape_task();
		obstacle_task();
		perimeter_task();
		navmode_task();
		seek_task();
		xlate_task();

		/* arbitrate and call motorcmd(); */
		 arbitrator();

		/* at user rate or 25 Hz */
		if (p_user_sensor_rate) wake_after(p_user_sensor_rate);
		else PERIOD(&t,40);
	}
}
```

Demo 7

Video
jBot: Cones

III. Advanced Navigation Modes



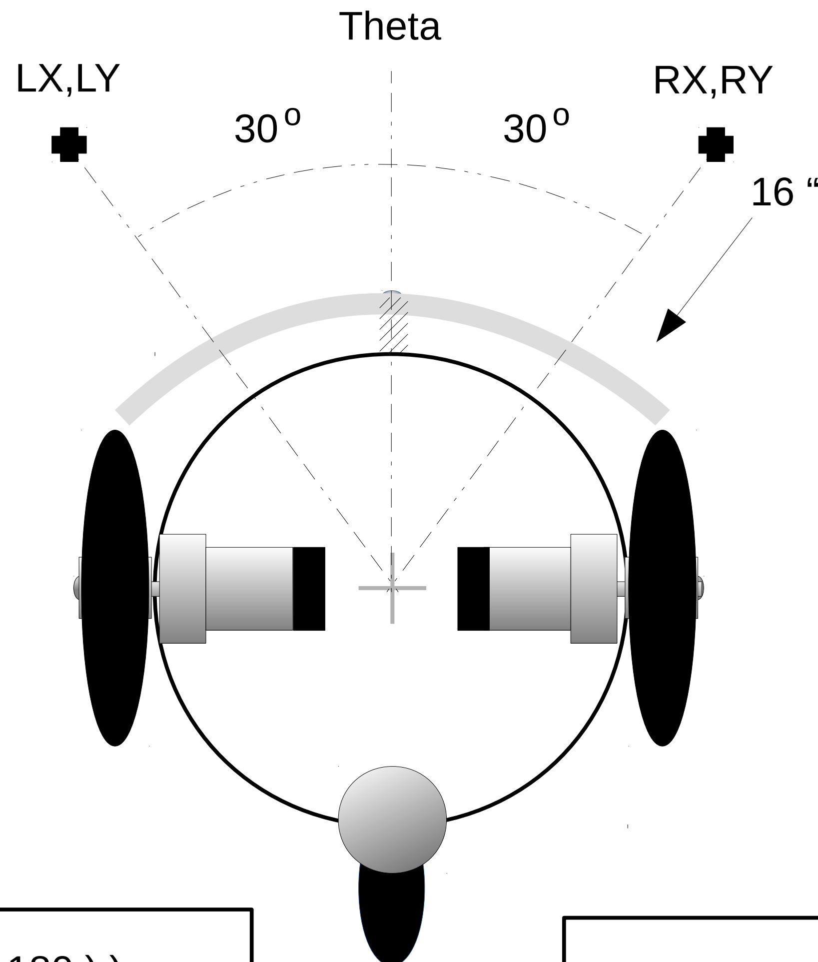
III. Advanced Navigation Modes

A. Boundary Detector

B. Slip-Stuck Detector

C. Concave Singularity Detector
(“Minnow Trap”)

A. Virtual Boundary Detectors

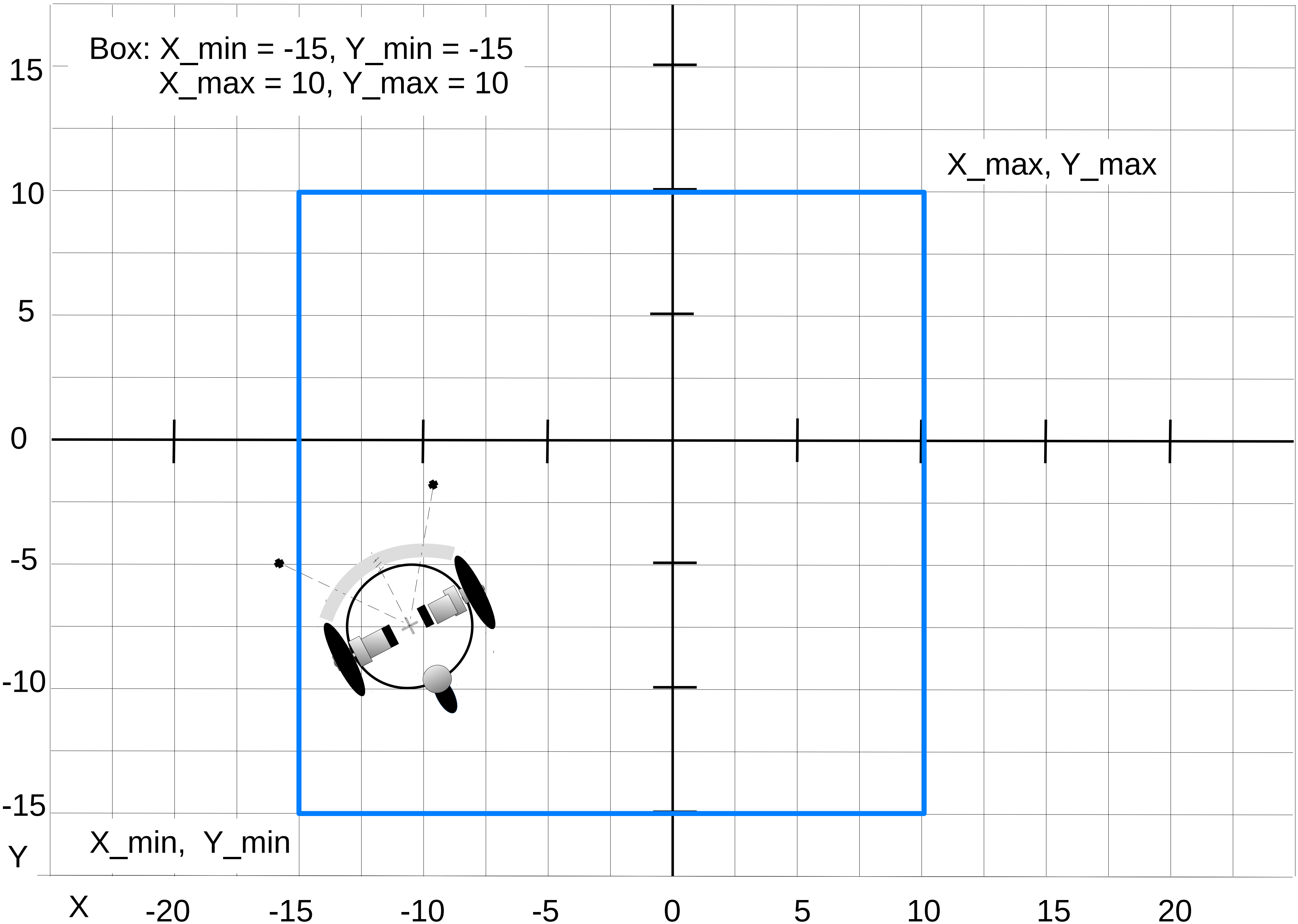


L_angle = Theta - (30 * (PI / 180))

LX = X_position + (sin (L_angle) * 16)
LY = Y_position + (cos (L_angle) * 16)

R_angle = Theta + (30 * (PI / 180))

RX = X_position + (sin (R_angle) * 16)
RY = Y_position + (cos (R_angle) * 16)



Box: X_min = -15, Y_min = -15
X_max = 10, Y_max = 10
X_max, Y_max
X_min, Y_min
15
10
5
0
-5
-10
-15
Y
X
-20
-15
-10
-5
0
5
10
15
20

Virtual Sensors: Boundary Detectors

```
int boundary ( float x, y )
{
      extern BOX box;

      if ( ( x < box.xmin ) || ( x > box.xmax ) )
            return TRUE;

      if ( ( y < box.ymin ) || ( y > box.ymax ) )
            return TRUE;

      return FALSE;
}
```

Demo 8

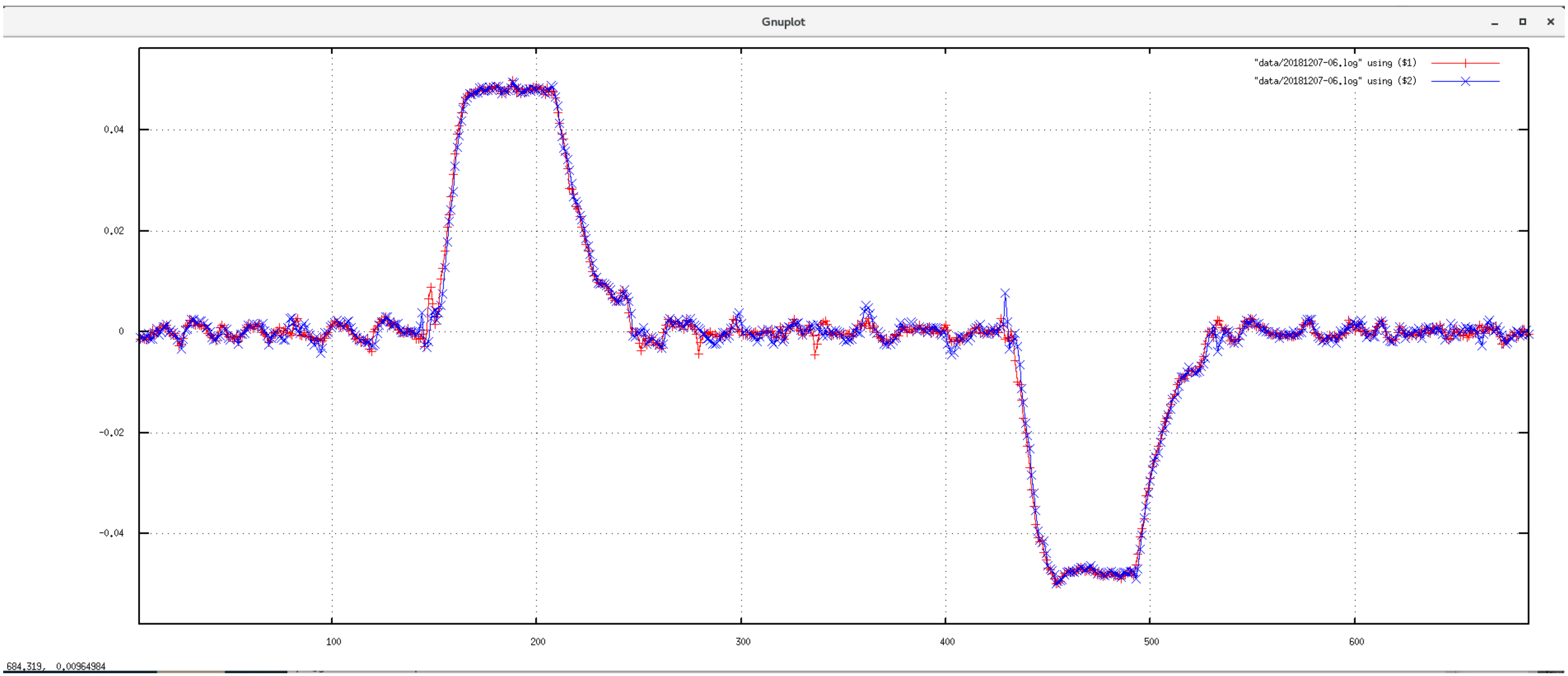
Live
RCAT: Boundary Detection

Video
RCAT: Hallway Boundary

B. Virtual Slip/Stuck Detector

Detecting and Getting Unstuck

wheel rate vs. gyro rate


Gnuplot
"data/20181207-06.log" using ($1)
"data/20181207-06.log" using ($2)
0.04
0.02
0
-0.02
-0.04
100
200
300
400
500
600
684.319, 0.00964984

```
int dif_count = 0;

void slip-stuck_behavior ( void )
{
        float rate_dif = wheel_rate - gyro_rate;

        if ( ( rate_dif > MAXRATEDIF )  ||  ( rate_dif < -MAXRATEDIF ) ) {

                dif_count++;
                if ( dif_count > MAXDIFCOUNT ) {
                        trigger_escape();
                }

        } else  dif_count = 0;
}
```

Demo 9

Live
RCAT: Virtual bumper

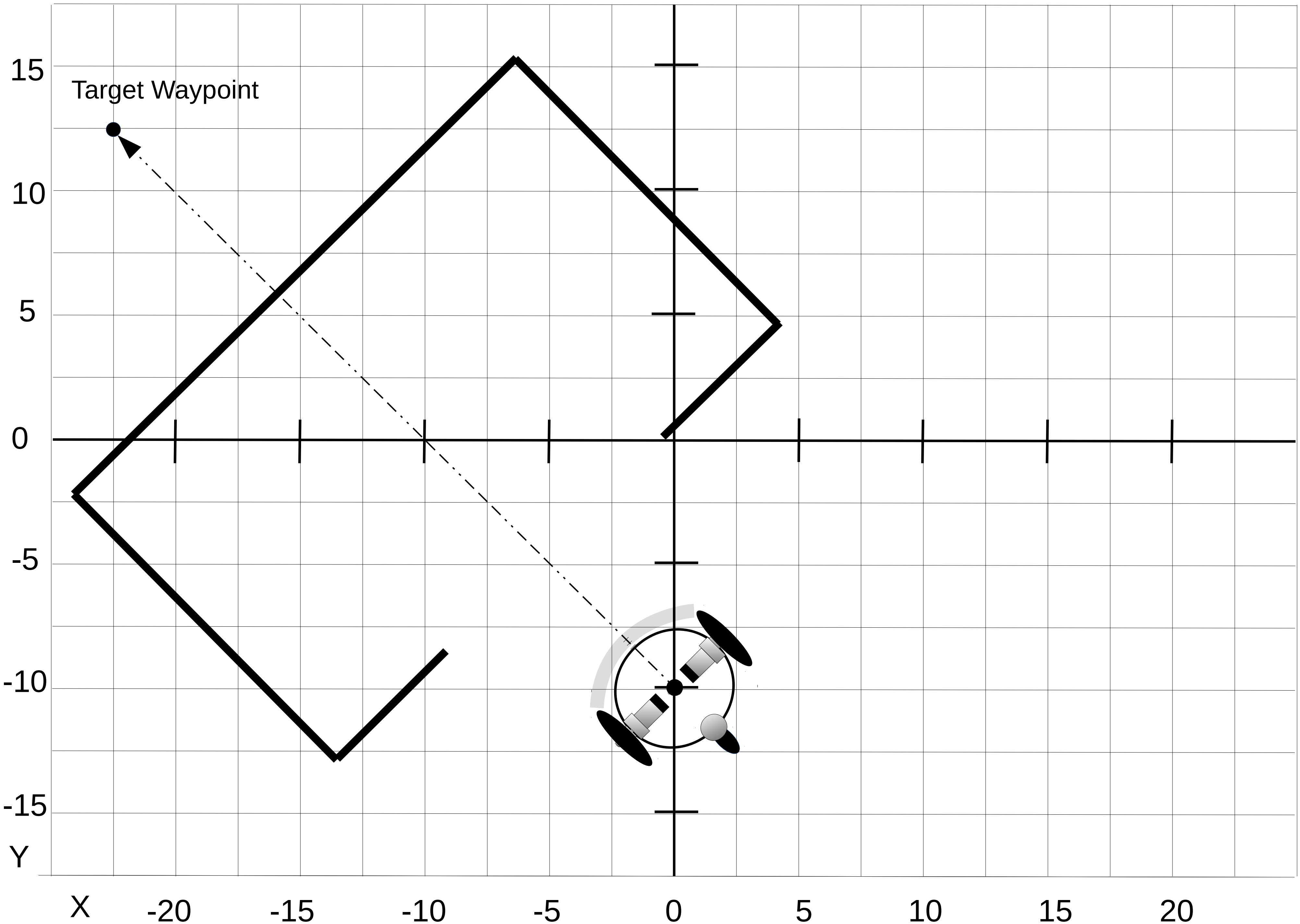
Video
jBot: Getting Unstuck

C. Virtual Concave Singularity Detector

Concave Waypoint Singularity:

(Minnow Trap)

Pose: X = 0, Y = -10, Z = -45



D10

Demo 10

Video
LegoBot: waypoint trap

```
void  navmode_behavior ( void )
{

        extern int perimeter_enable;       // enable perimeter following

        if (  perimeter_enable == FALSE {

                if ( bearing == 180 ) perimeter_enable = TRUE;
        }

        if ( perimeter_enable == TRUE ) {

                if ( bearing == 0 ) perimeter_enable = FALSE;
        }
}
```


Central Receiving
UNT College of Information
Discovery Park
University of North Texas Discovery Park
Discovery Park Library
Department of Materials Science and...
Computer Science and Engineering
UNT Discovery Park Bus Stop
UNT Lot 91
77
77
N Elm St

D11

Demo 11

Video
jBot @ TI

```
#define CBLK_SIZE 6                                  // number of subsumption behaviors

CMDBLOCK *cmdblocks [ CBLK_SIZE ] = {               // subsumption behavior priority order
            escape,                                  // highest priority
            ir,
            sonar,
            perimeter,
            navigate,
            default;                                 // lowest priority
}
```

```
void arbitrator ( void )  {                          // subsumption arbitrator

      int i;

      for ( i = 0; i < CBLK_SIZE; i++ ) {
            if (cmdblocks [i]->flag) break;
      }

      bot_velocity = cmdblocks[i]->cmd;
      bot_rotate    = cmdblocks[i]->arg;

      motor_command ( bot_velocity, bot_rotate );
}
```