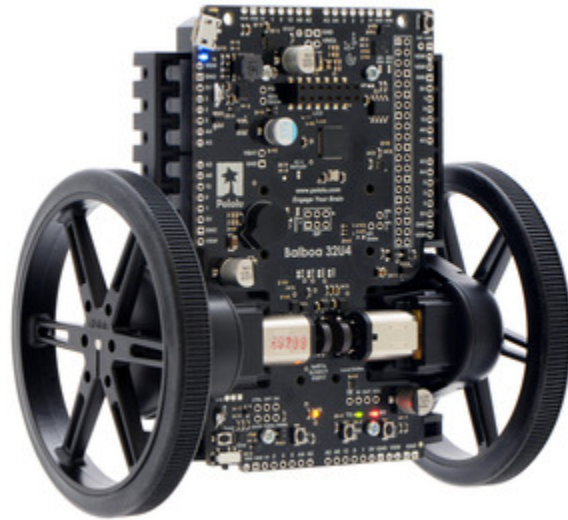


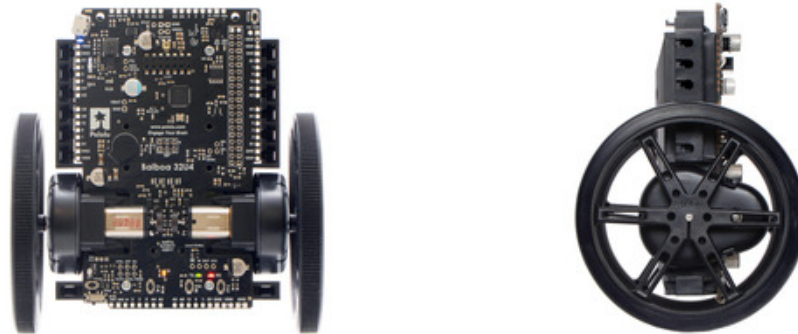
Pololu Balboa 32U4 Balancing Robot User's Guide



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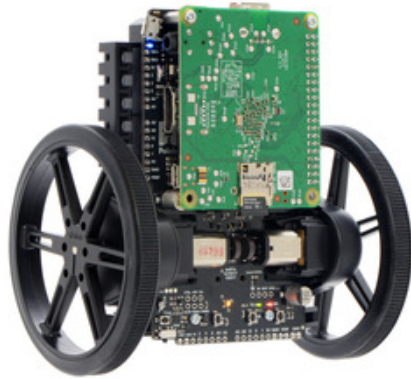
1. Overview

The Balboa 32U4 is a highly integrated balancing robot that is both programmable and customizable.



Like our **A-Star 32U4 programmable controllers** [<https://www.pololu.com/category/149/a-star-programmable-controllers>], the Balboa 32U4 control board is built around a USB-enabled Atmel ATmega32U4 AVR microcontroller, and it ships preloaded with an Arduino-compatible bootloader. The control board features two H-bridge motor drivers, as well as quadrature encoders and a complete inertial measurement unit (accelerometer, gyro, and magnetometer) that allows it to determine its orientation – essential for balancing. It also includes a powerful 5 V switching step-down regulator that can supply up to 2 A continuously, along with a versatile power switching and distribution circuit. Three on-board pushbuttons offer a convenient interface for user input, while indicator LEDs, a buzzer, and a connector for an optional LCD allow the robot to provide feedback.

The Balboa 32U4 can be used either as a standalone control solution or as a base for a more powerful Raspberry Pi controller. Its on-board connector and mounting holes allow a compatible Raspberry Pi (Model B+ or newer, including **Pi 3 Model B** [<https://www.pololu.com/product/2759>] and **Model A+** [<https://www.pololu.com/product/2760>]) to plug directly into the control board. Integrated level shifters make it easy to set up I²C communication and interface other signals between the two controllers, and the control board automatically supplies 5 V power to an attached Raspberry Pi. In this setup, the Raspberry Pi can handle the high-level robot control while relying on the Balboa 32U4 control board for low-level tasks, like running motors, reading encoders, and interfacing with other analog or timing-sensitive devices.



**Balboa 32U4 Balancing Robot with
80×10mm wheels and a Raspberry Pi 1
Model A+.**



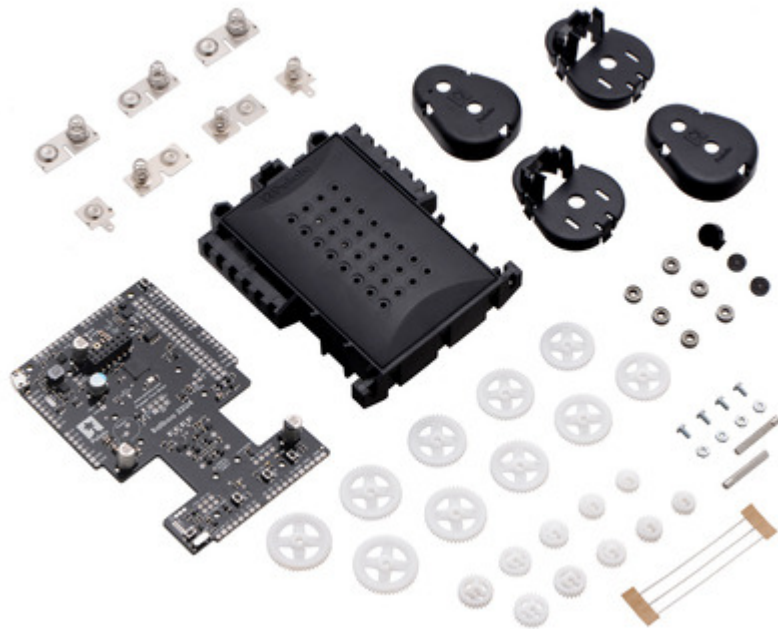
**Balboa 32U4 Balancing Robot with
80×10mm wheels and a Raspberry Pi 3
Model B.**

Many of the ATmega32U4 I/O lines are broken out to 0.1"-spaced through-holes along the edges of the board, and the board's power rails are also accessible, enabling sensors and other peripherals to easily be connected.

A software add-on is available that makes it easy to program a Balboa 32U4 robot from the Arduino environment, and we have Arduino libraries and example sketches to help get you started. A **USB A to Micro-B cable** [<https://www.pololu.com/product/2072>] (not included) is required for programming.

1.1. Included components

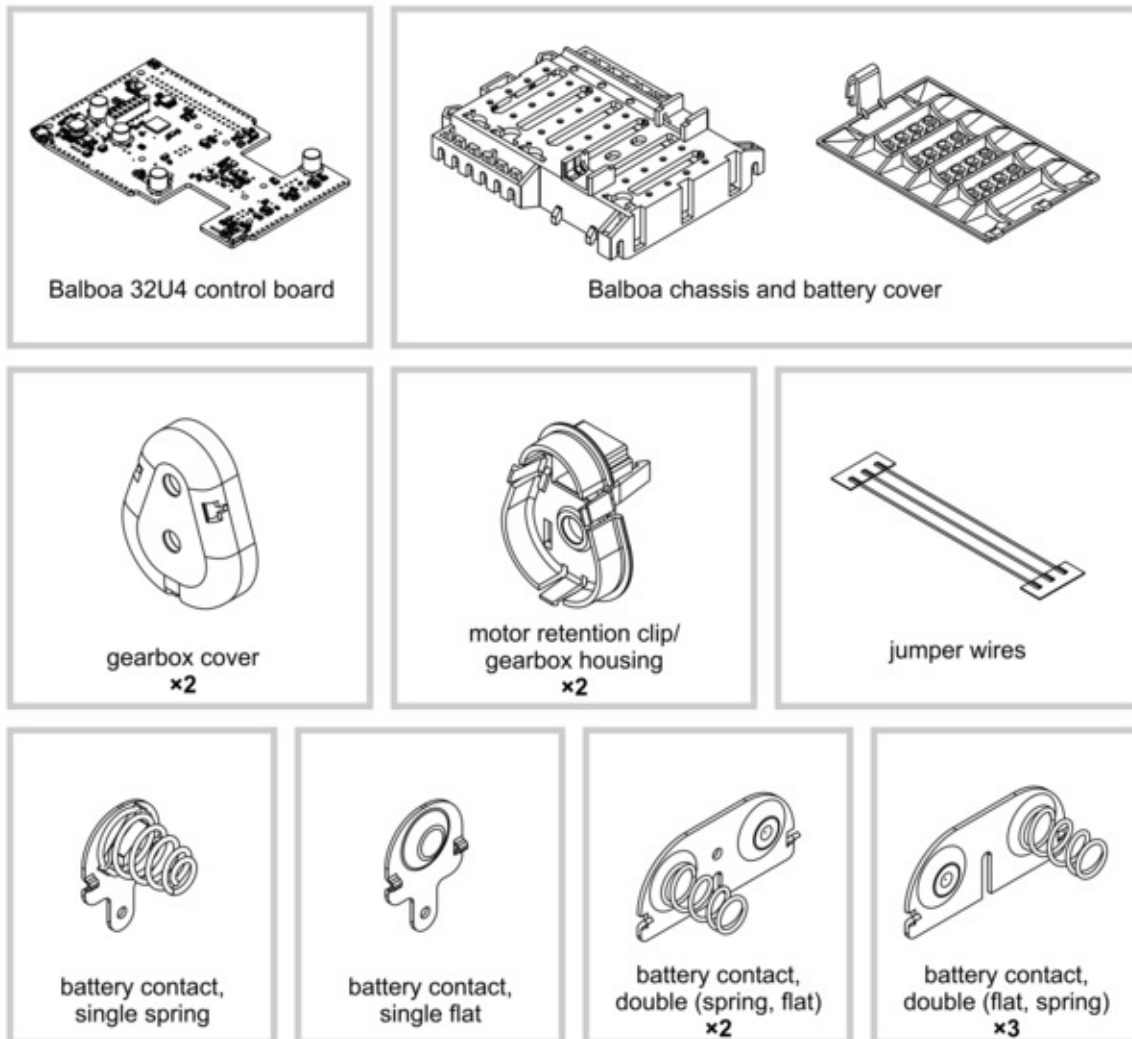
The Balboa 32U4 is available as a **kit** [<https://www.pololu.com/product/3575>] that requires assembly and soldering. The kit includes the following components:


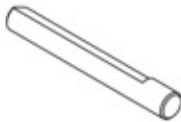
















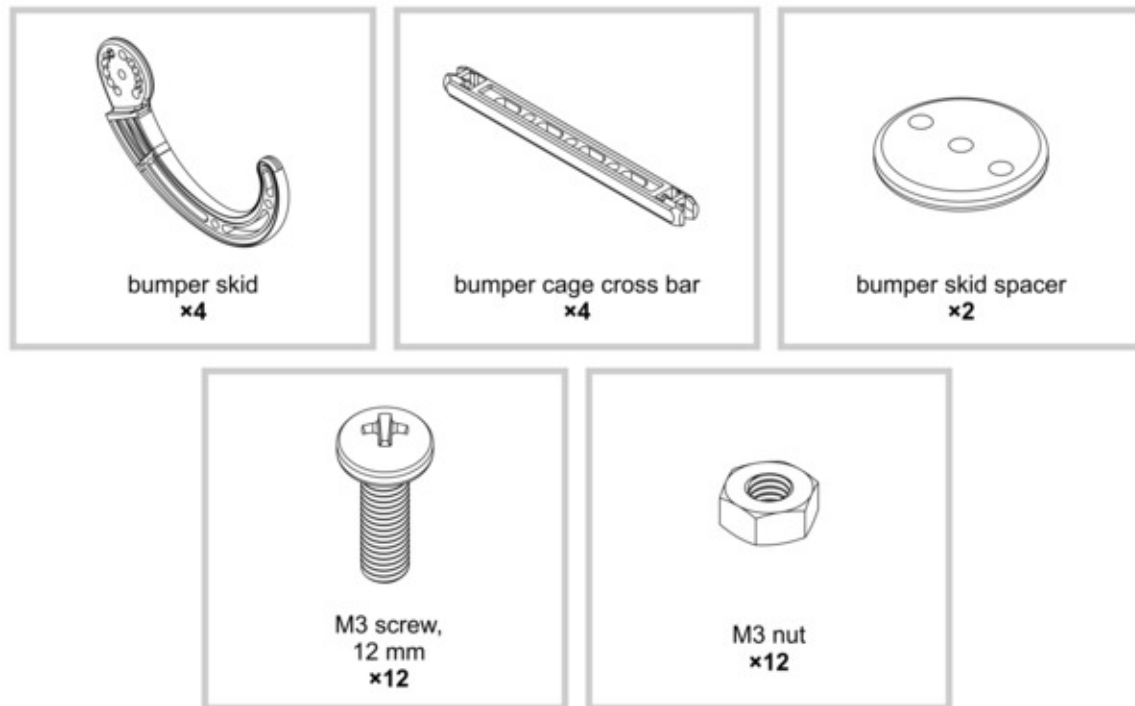
- Balboa core chassis
 - battery box and cover
 - two motor retention clips/gearbox housings
 - two gearbox covers
 - six 683 ball bearings
 - two 3 mm D-shafts
 - ten plastic pinion gears (small – two each with 17, 19, 21, 23, and 25 teeth)
 - ten plastic output gears (large – two each with 41, 43, 45, 47, and 49 teeth)
 - battery terminals
- **Balboa 32U4 control board** [<https://www.pololu.com/product/3576>] and related parts:
 - **buzzer** [<https://www.pololu.com/product/1484>]



- jumper wires (for soldering motors to the main board)
- two **magnetic encoder discs** [<https://www.pololu.com/product/2599>] (12 CPR)
- four 3/16" #2-56 screws and nuts
- **bumper cage kit** [<https://www.pololu.com/product/3574>], which includes:
 - four bumper skids
 - four bumper cage cross bars
 - two bumper skid spacers
 - twelve 12 mm M3 screws and nuts



 <p>683 ball bearing x6</p>	 <p>3 mm D-shaft x2</p>	 <p>#2-56 screw, 3/16" x4</p>	 <p>#2-56 nut x4</p>
 <p>buzzer</p>	 <p>magnetic encoder disc x2</p>	 <p>pinion gear, 17-tooth x2</p>	 <p>pinion gear, 19-tooth x2</p>
 <p>pinion gear, 21-tooth x2</p>	 <p>pinion gear, 23-tooth x2</p>	 <p>pinion gear, 25-tooth x2</p>	 <p>gear, 41-tooth x2</p>
 <p>gear, 43-tooth x2</p>	 <p>gear, 45-tooth x2</p>	 <p>gear, 47-tooth x2</p>	 <p>gear, 49-tooth x2</p>



The robot and chassis kit might include extra parts like jumper wires, screws, and nuts, so do not be concerned if you have some leftover hardware after assembling your Balboa.

1.2. What you will need

You will need a number of additional components and tools to complete your Balboa robot, the most important of which are motors and wheels. Since the Balboa 32U4 robot kit works with a variety of motors and wheels, **motors and wheels are not included**; this means you can choose your own to personalize your robot.

Motor selection

The Balboa uses **two** micro metal gearmotors to drive external 2-gear gearboxes that further increase the gear ratio and support the weight of the robot with ball bearings rather than the motor shafts themselves. The Balboa kit gives you five reduction options to choose from when assembling your robot (ranging from 1.64:1 to 2.88:1), and you can further customize the gear ratio based on which micro metal gearmotor you choose for your robot. The integrated quadrature encoders require gearmotors **with extended motor shafts**, and we specifically recommend the **30:1 HPCB** [<https://www.pololu.com/product/3072>], **50:1 HPCB** [<https://www.pololu.com/product/3073>], or **75:1 HPCB** [<https://www.pololu.com/product/3074>] versions. Note that torque is approximately proportional to the gear ratio and speed is inversely proportional, so as the gear ratio gets bigger, the torque increases while the speed decreases.



A look inside the external gearbox on the Balboa 32U4 Balancing Robot.



Pololu

Micro metal gearmotor HPCB with extended motor shaft.

The kit includes magnetic encoder discs, and the encoder sensors are built into the Balboa 32U4 control board, so you do **not** need to order encoders with your motors.

Wheel selection

We recommend using the Balboa with 80×10mm Pololu wheels, which are available in five colors — **black** [<https://www.pololu.com/product/1430>], **red** [<https://www.pololu.com/product/1431>], **yellow** [<https://www.pololu.com/product/1432>], **blue** [<https://www.pololu.com/product/1433>], and **white** [<https://www.pololu.com/product/1434>] — but our larger **90×10mm wheels** [<https://www.pololu.com/product/1435>] and smaller **70×8mm wheels** [<https://www.pololu.com/product/1425>] are also options if you know what you are doing (note that the 70×8mm wheels only offer a few millimeters of clearance when the robot is balancing).

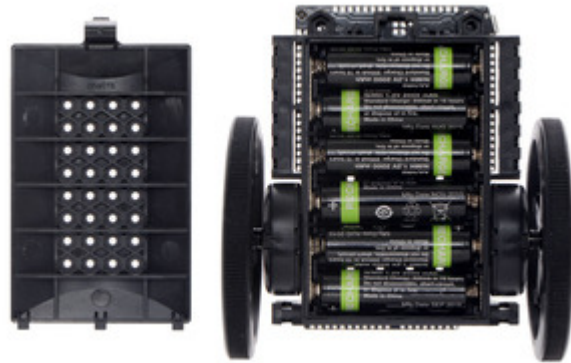


Pololu Wheel 80×10mm Pair – Red.

These additional items are also needed for using and assembling the Balboa 32U4 robot kit:

Other things you will need

- six **AA batteries** [<https://www.pololu.com/product/1003>]. The Balboa works with both alkaline and NiMH batteries, though we recommend rechargeable NiMH cells.
- **USB A to Micro-B cable** [<https://www.pololu.com/product/2072>] to connect the board to your computer for programming and debugging
- soldering iron and solder (we recommend one with adjustable temperature control like the **Hakko FX-888D Digital Soldering Station** [<https://www.pololu.com/product/2779>])
- small Phillips screwdriver
- **wire cutter** [<https://www.pololu.com/product/159>] for trimming leads



Balboa 32U4 Balancing Robot with battery cover removed.

Optional tools


- **small pair of pliers** [<https://www.pololu.com/product/150>]
- **wire stripper** [<https://www.pololu.com/product/1923>], for adding wires for peripherals

- tape or small clamps (for holding parts together when soldering)
- small 2 mm slotted screwdriver for adjusting the LCD contrast

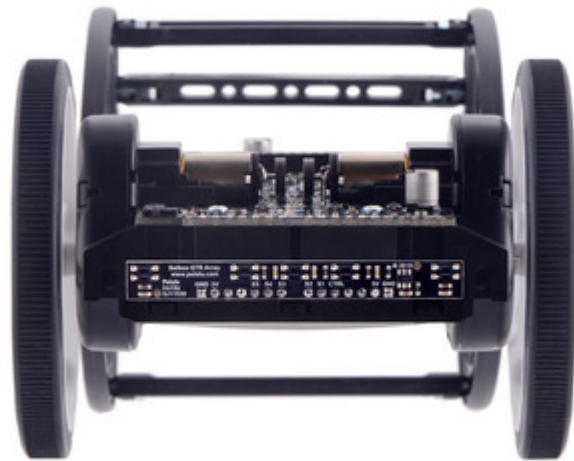
Optional accessories

You might also consider getting these for your Balboa:

- an **8×2 character LCD** [<https://www.pololu.com/product/356>] and **low-profile 2×7 male header** [<https://www.pololu.com/product/2663>] so you can connect it to the female LCD header on the Balboa
- a compatible Raspberry Pi (Model B+ or newer, including **Pi 3 Model B** [<https://www.pololu.com/product/2759>] and **Model A+** [<https://www.pololu.com/product/2760>]) and a **2×20 female header** [<https://www.pololu.com/product/1037>], **standoffs** [<https://www.pololu.com/product/2713>], **screws** [<https://www.pololu.com/product/1968>], and **nuts** [<https://www.pololu.com/product/1967>] for mounting it

-  The Balboa is intended to be used with our **standoffs with 4 mm threads** [<https://www.pololu.com/product/2713>]. Our standoffs with longer (6 mm) threads will interfere with the chassis.

- **5-Channel Reflectance Sensor Array** [<https://www.pololu.com/product/3577>] for identifying changes in reflectance on the ground directly underneath the Balboa (like detecting or following a black line on a white background)
- other **sensors** [<https://www.pololu.com/category/7/sensors>], such as **optical** [<https://www.pololu.com/category/79/sharp-distance-sensors>] or **sonar range finders** [<https://www.pololu.com/category/78/sonar-range-finders>]
- **connectors and jumper wires** [<https://www.pololu.com/category/19/connectors>], for connecting additional sensors and components
- battery charger, if you are using



Center-aligned mounting option for the 5-Channel reflectance sensor array for Balboa.

rechargeable batteries; since the Balboa just uses ordinary AA batteries, we recommend basic AA chargers (into which you stick the individual cells) available at most general electronics stores, though we carry a much fancier **iMAX-B6AC V2 balance charger/discharger** [<https://www.pololu.com/product/2588>] that can be also used for this

1.3. Supported operating systems

The Balboa 32U4 control board can be programmed using Microsoft Windows 11, 10, 8.1, 8, 7, Vista, XP (with Service Pack 3), Linux, and macOS 10.11 or later.

2. Contacting Pololu

We would be delighted to hear from you about any of your projects and about your experience with the Balboa 32U4. You can **contact us** [<https://www.pololu.com/contact>] directly or post on our **forum** [<http://forum.pololu.com/>]. Tell us what we did well, what we could improve, what you would like to see in the future, or anything else you would like to say!

3. Balboa 32U4 in detail

3.1. Microcontroller

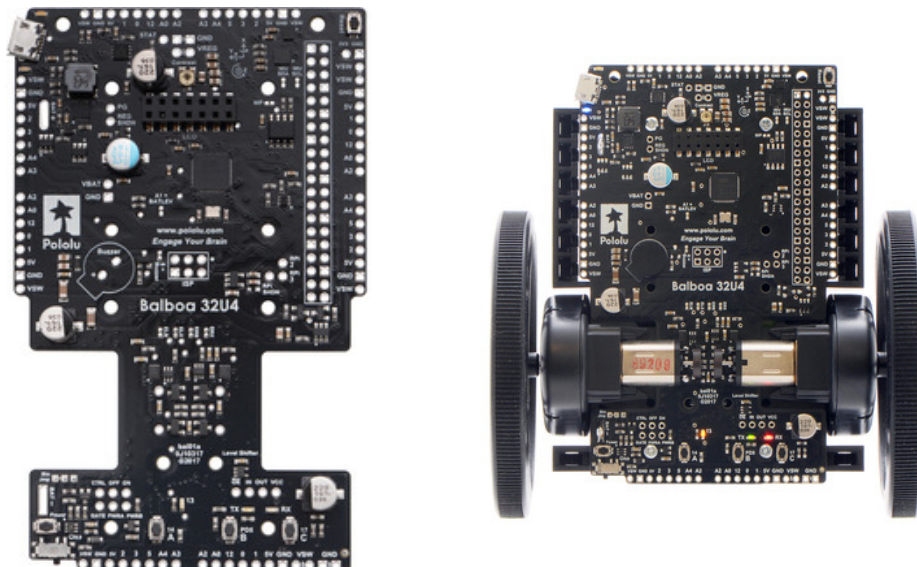
Like our **A-Star 32U4 programmable controllers** [<https://www.pololu.com/category/149/a-star-programmable-controllers>], the Balboa 32U4 control board features an integrated, USB-enabled ATmega32U4 AVR microcontroller from Atmel, clocked by a precision 16 MHz crystal oscillator. This is the same microcontroller and clock frequency used in the **Arduino Leonardo** [<https://www.pololu.com/product/2192>] and **Arduino Micro** [<https://www.pololu.com/product/2188>].

The control board includes a USB Micro-B connector that can be used to connect to a computer's USB port via a **USB A to Micro-B cable** [<https://www.pololu.com/product/2072>] (not included). The USB connection can be used to transmit and receive data from the computer and program the board over USB. The USB connection can also provide power for the microcontroller and most of the other hardware on the board (but not motor power); see **Section 3.6** for more details.

The control board's ATmega32U4 comes preloaded with the Arduino-compatible **A-Star 32U4 USB bootloader** [<https://www.pololu.com/docs/0J70/9>], which allows it to be easily programmed using the Arduino IDE. For more information about programming the Balboa 32U4, see **Section 5**.

The board also has a 6-pin ISP header that allows it to be programmed with an external programmer, such as our **USB AVR programmer** [<https://www.pololu.com/product/3172>]. Pin 1 of the header is indicated with a small white dot and has an octagonal shape.

3.2. User interface



LEDs

The Balboa 32U4 control board has five indicator LEDs, three of which are user-controllable:

- A **yellow** user LED is connected to Arduino digital pin 13, or PC7. You can drive this pin **high** in a user program to turn this LED on. The **A-Star 32U4 Bootloader** [<https://www.pololu.com/docs/0J70/9J>] fades this LED on and off while it is waiting for a sketch to be loaded.
- A **green** user LED is connected to Arduino pin 30, or PD5, and lights when the pin is driven **low**. While the board is running the A-Star 32U4 Bootloader or a program compiled in the Arduino environment, it will flash this LED when it is *transmitting* data via the USB connection.
- A **red** user LED is connected to Arduino pin 17, or PB0, and lights when the pin is driven **low**. While the board is running the A-Star 32U4 Bootloader or a program compiled in the Arduino environment, it will flash this LED when it is *receiving* data via the USB connection.

These three user LEDs are all located near the bottom of the board, and the Balboa32U4 library contains functions that make it easier to control them (see **Section 6**). All three user LED control lines are also LCD data lines, so you will see them flicker when you update the LCD. The green and red user LEDs also share I/O lines with pushbuttons (see below).

The remaining two LEDs are power indicators, and they are located in the top left corner of the board near the USB connector:

- A **blue** power LED indicates when the controller is receiving power from the Balboa's batteries (the power switching circuit must be turned on).
- A **green** power LED indicates when the USB bus voltage (VBUS) is present.

Pushbuttons

The Balboa 32U4 control board has five pushbuttons: a **power button** in the bottom left corner, a **reset button** in the top right corner, and **three user pushbuttons** located along the bottom edge. The user pushbuttons, labeled A, B, and C, are on Arduino pin 14 (PB3), pin 30 (PD5), and pin 17 (PB0), respectively. Pressing one of these buttons pulls the associated I/O pin to ground through a resistor.

The three buttons' I/O lines are also used for other purposes: pin 14 is MISO on the SPI interface, pin 30 and pin 17 control the green and red user LEDs, and all three pins are LCD data lines. Although these uses require the pins to be driven by the AVR (or SPI slave devices in the case of MISO), resistors in the button circuits ensure that the Balboa 32U4 control board will not be damaged even if the corresponding buttons are pressed at the same time, nor will SPI or LCD communications be disrupted. The functions in the Balboa32U4 library take care of configuring the pins, reading and

debouncing the buttons, and restoring the pins to their original states.

Buzzer

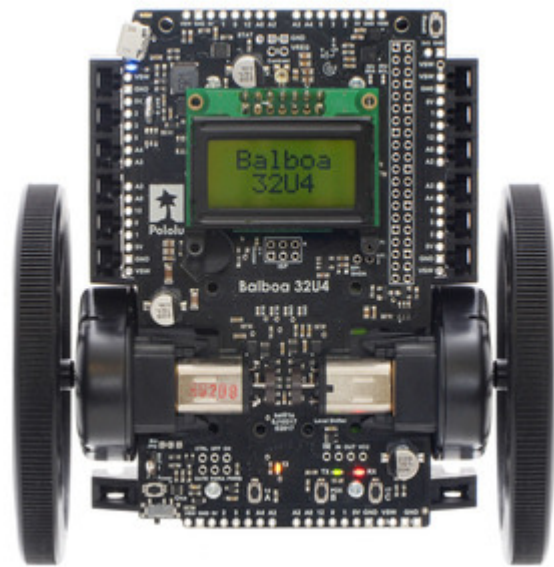
The **buzzer** [<https://www.pololu.com/product/1484>] included with the Balboa 32U4 control board can be soldered into the designated through-holes and used to generate simple sounds and music. By default, it is connected to digital pin 6 (which also serves as OC4D, a hardware PWM output from the AVR's 10-bit Timer4). If you alternate between driving the buzzer pin high and low at a given frequency, the buzzer will produce sound at that frequency. You can play notes and music with the buzzer using functions in the Balboa32U4 library. If you want to use pin 6 for an alternate purpose, you can disconnect the buzzer circuit by cutting the surface-mount jumper next to the buzzer.

LCD header

The Balboa 32U4 control board has a 2×7 header where you can connect an **8×2 character LCD** [<https://www.pololu.com/product/356>] with a **low-profile male header** [<https://www.pololu.com/product/2663>] (or any other LCD with the common **HD44780 parallel interface** [<https://www.pololu.com/file/0J71/DMC50448N-AAE-AD.pdf>] (109k pdf)). You can adjust the LCD contrast with the potentiometer directly above the LCD connector. We recommend using a 2 mm slotted screwdriver to adjust the contrast.

The Balboa32U4 library provides functions to display data on a connected LCD. It is designed to gracefully handle alternate use of the LCD data lines by only changing pin states when needed for an LCD command, after which it will restore them to their previous states. This allows the LCD data lines to be used for other functions (such as pushbutton inputs and LED drivers).

Note that the control board is not designed to allow both an LCD and a Raspberry Pi to plug into it at the same time. However, having a Raspberry Pi header (not included) soldered to the board should not interfere with mounting an LCD, and the on-board LCD connector should not interfere with mounting a Raspberry Pi.



Balboa 32U4 Balancing Robot with 80×10mm wheels and LCD.

3.3. Motors

Motor drivers

Two on-board Texas Instruments DRV8838 motor drivers power the Balboa's two micro metal gearmotors. Four Arduino pins are used to control the drivers:

- **Digital pin 15**, or PB1, controls the **right motor direction** (LOW drives the motor forward, HIGH drives it in reverse).
- **Digital pin 16**, or PB2, controls the **left motor direction**.
- **Digital pin 9**, or PB5, controls the **right motor speed** with PWM (pulse width modulation) generated by the ATmega32U4's Timer1.
- **Digital pin 10**, or PB6, controls the **left motor speed** with PWM.

Note that “forward” refers to the rotation direction that would cause a balancing Balboa to move in the direction its battery cover is facing.

For more information about the drivers, see the **DRV8838 datasheet** [<https://www.pololu.com/file/0J806/drv8838.pdf.redirect>] (1k redirect). We also sell a **carrier board** [<https://www.pololu.com/product/2990>] for this driver.

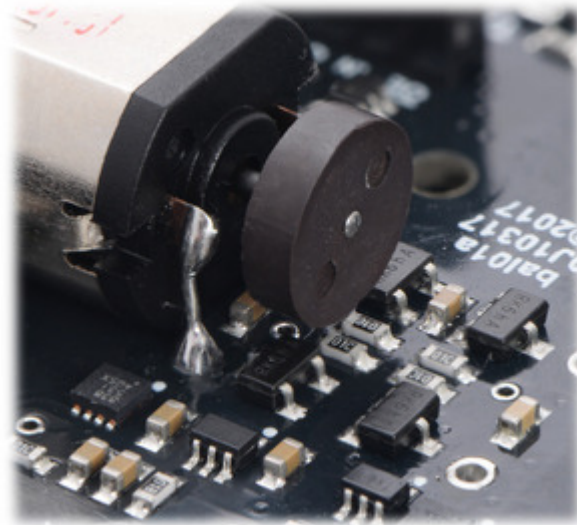
The Balboa32U4 library provides functions that allow you to easily control the motors, and it can optionally take care of flipping a direction signal for you if you accidentally soldered in a motor backwards (see **Section 6**).



As your batteries run out, the voltage supplied to the motor drivers (VSW) will decrease, which will make the motors slower. It is possible to account for this in your code by monitoring the battery voltage (see **Section 3.6**) or using the encoders and other sensors to monitor the movement of the robot.

3.4. Quadrature encoders

Each drive motor on the Balboa 32U4 has a corresponding quadrature encoder system consisting of a magnetic disc attached to the extended motor shaft and a pair of Hall effect sensors mounted on the control board. Other than the sensor orientation, these encoders work similarly to our **magnetic encoder kits for micro metal gearmotors** [<https://www.pololu.com/product/3081>]. They can be used to track the rotational speed and direction of the robot's wheels.

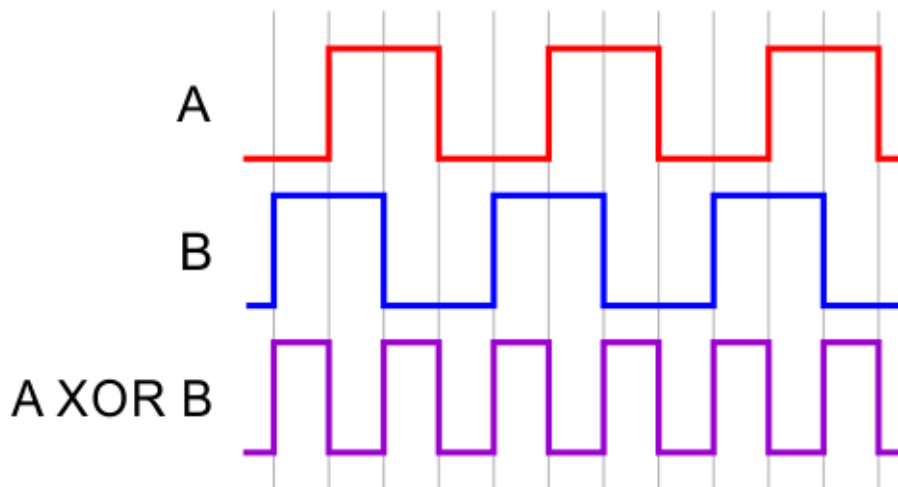
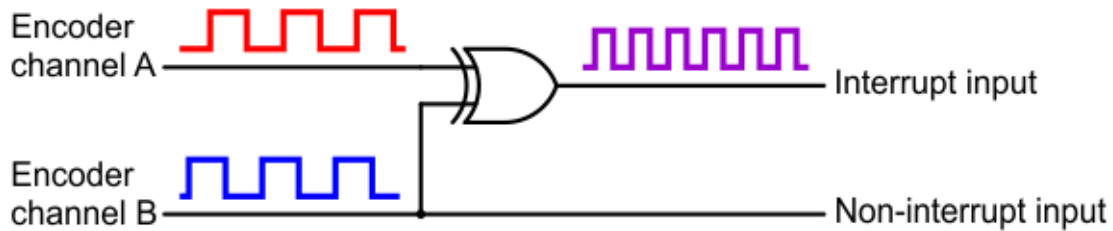


Balboa encoder, showing the magnetic disc and sensors (with one motor removed).

The encoders provide a resolution of 12 counts per revolution of the motor shaft when counting both edges of both channels. To compute the counts per revolution of the wheels, calculate the total gear ratio of the gearmotors and the Balboa chassis's gearboxes combined by multiplying their individual gear ratios, then multiply the result by 12. For example, if **50:1 motors** [<https://www.pololu.com/product/3073>] (which have gear ratios more accurately specified as 51.45:1) are used along with the plastic gears that give an additional 2.88:1 reduction, the encoders provide $51.45 \times 2.88 \times 12 \approx 1778$ **CPR**.

Quadrature encoder transitions are often detected by monitoring both encoder channels directly. However, since transitions on the Balboa's encoders can occur at high frequencies (several thousand per second) when its motors are running, it is necessary to use the AVR's pin change interrupts or external interrupts to read the encoders. To reduce the required number of interrupt pins, the Balboa 32U4 control board XORs together both channels of each encoder and connects the resulting signal to an interrupt pin, while channel B of each encoder is connected to a non-interrupt pin:

- **Digital pin 7**, or PE6, reads the **right encoder XORed signal** using external interrupt INT6.
- **Digital pin 8**, or PB4, reads the **left encoder XORed signal** using pin change interrupt PCINT4.
- **Digital pin 23** (analog pin 5), or PF0, reads the **right encoder channel B**.
- Pin **PE2** reads the **left encoder channel B**.

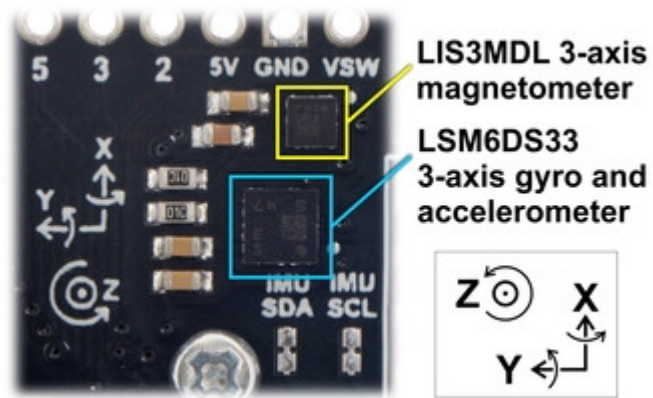


The XORed signal and the channel B signal can be used to reconstruct the channel A signal by simply XORing them again: $(A \text{ XOR } B) \text{ XOR } B = A$. For both encoders, channel B leads channel A when the motor is rotating in the forward direction; that is, B rises before A rises and B falls before A falls. (The waveforms in the diagram above would be produced by forward rotation.) Note that “forward” refers to the rotation direction that would cause a balancing Balboa to move in the direction its battery cover is facing.

The Balboa32U4 library provides appropriate interrupt service routines and functions for reading the encoders and keeping track of their counts (see [Section 6](#)).

3.5. Inertial sensors

Balboa 32U4 includes on-board inertial sensors that allow it to determine its own orientation by implementing an inertial measurement unit (IMU); this is key to Balboa's balancing ability. The first chip, an ST **LSM6DS33** [<https://www.pololu.com/product/2736>], combines a 3-axis accelerometer and 3-axis gyro into a single package. The second chip is an ST **LIS3MDL** [<https://www.pololu.com/product/2737>] 3-axis magnetometer.



The Balboa 32U4's IMU and compass chips.

Both sensor chips are connected to the board's I²C bus by default. Level shifters built into the control board allow the ATmega32U4, operating at 5 V, to communicate with the 3.3 V sensors. If a Raspberry Pi is plugged into the control board, its I²C pins are connected to the 3.3 V side of the bus as well. (See **Section 3.8** for more information about the Raspberry Pi interface.)

The Balboa32U4 library (see **Section 6**) includes example programs that demonstrate how to use the sensors, including a balancing demo. In addition, the sensor ICs on Balboa 32U4 are the same as those on our **MinIMU-9 v5** [<https://www.pololu.com/product/2738>], so software written for the MinIMU-9 (such as our **Arduino AHRS example** [<https://github.com/pololu/minimu-9-ahrs-arduino>]) can also be adapted to work on Balboa.

Please note that the LIS3MDL magnetometer can be affected by magnetic fields from the Balboa itself. These include magnets in the motors and encoders, electrical currents through the board, and hard iron distortions from metal (probably mostly from the batteries). The magnetometer is positioned as far away from the motors as possible to avoid interference from them, but we have found that hard iron distortions still influence the readings significantly, making it difficult to accurately determine the Balboa's absolute heading based on the raw magnetometer data. This **post on the Pololu forum** [<https://forum.pololu.com/t/correcting-the-balboa-magnetometer/14315>] details a technique for correcting for hard iron distortions, making it possible to use of the magnetometer as a compass for navigation in environments that are not dominated by magnetic interference.

For more information on the sensors and how to use them, see the **LSM6DS33 datasheet** [<https://www.pololu.com/file/0J1087/LSM6DS33.pdf>] (1MB pdf) and **LIS3MDL datasheet** [<https://www.pololu.com/file/0J1089/LIS3MDL.pdf>] (2MB pdf).

3.6. Power

The Balboa 32U4 control board includes battery terminal connections that provide access to power from the Balboa chassis's six-AA battery compartment. We recommend using rechargeable AA NiMH cells, which results in a nominal voltage of 7.2 V (1.2 V per cell). You can also use alkaline cells, which would nominally give you 9 V.

The negative battery voltage is connected to GND. The positive battery voltage is designated **VBAT**. VBAT feeds into a reverse protection circuit and then a power switching circuit controlled by the on-board pushbutton or slide switch. The output of the power switching circuit is designated **VSW**.

VSW provides power to the motors through the on-board DRV8838 motor drivers, so the motors can only operate if the batteries are installed and the power switch circuit is on.

The reverse protected and switched battery voltage on VSW can be monitored through a voltage divider that is connected to **analog pin 1** (PF6). The divider outputs a voltage that is equal to one third of the battery voltage, which will be safely below the ATmega32U4's maximum analog input voltage of 5 V as long as the battery voltage is less than 15 V (though the maximum voltage for the board is still limited to 10.8 V by the DRV8838 motor driver). The `readBatteryMillivolts()` function in the Balboa32U4 library can be used to determine the battery voltage from this reading.

Power switch circuit

The Balboa 32U4 control board uses the patented latching circuit from the **Pololu pushbutton power switch** [<https://www.pololu.com/product/2808>], which provides a solid-state power switch for your robot controlled with the on-board pushbutton. By default, this pushbutton can be used to toggle power: one push turns on power and another turns it off. Alternatively, a separate pushbutton can be connected to the **PWRA** and **PWRB** pins and used instead. Multiple pushbuttons can be wired in parallel for multiple control points, and each of the parallel pushbuttons, including the one on the board itself, will be able to turn the switch on or off. **The latching circuit performs some button debouncing, but pushbuttons with excessive bouncing (several ms) might not function well with it.**



For proper pushbutton operation, the board's slide switch should be left in its **Off** position. (Sliding the switch to the On position will cause the board power to latch on, and the switch must be returned to the Off position before the board can be turned off with the pushbutton.)

Alternatively, to disable the pushbutton, you can cut the button jumper labeled **Btn Jmp**; this transfers control of the board's power to the on-board slide switch instead. A separate slide or toggle switch can be connected to the **GATE** pin and used instead.

The power switch circuit also offers several alternate pushbutton connection options that result in push-on-only or push-off-only operation, and additional inputs enable further power control options like allowing your robot to turn off its own power. These advanced control options are available through the button connection pins and four control inputs:

PIN	Description
PWRA	Connect through momentary switch to pin “PWRB” for standard push-on/push-off operation. Connect through momentary switch to ground for on-only operation.
PWRB	Connect through momentary switch to pin “PWRA” for standard push-on/push-off operation.
ON	A high pulse (> 1 V) on this pin turns on the switch circuit. <i>This pin only functions when pushbutton operation is enabled (i.e. the button jumper has not been cut).</i>
OFF	A high pulse (> 1 V) on this pin turns off the switch circuit (e.g. allowing a powered device to shut off its own power). <i>This pin only functions when pushbutton operation is enabled.</i>
CTRL	With pushbutton operation enabled, this pin directly determines the state of the switch circuit. A high pulse (> 1 V) on this pin turns on the switch; a low pulse (e.g. driving the pin low with a microcontroller output line or pushing a button connected from this pin to ground) turns the switch off. Leave this pin disconnected or floating when not trying to set the switch state. <u>Note that this pin should not be driven high at the same time the “OFF” pin is driven high.</u>
GATE	With pushbutton operation <u>disabled</u> (button jumper cut), this pin controls the state of the switch circuit: driving it low turns the switch on, while letting it float turns the switch off. Connect through slide or toggle switch to ground for on/off operation. Leave this pin disconnected or floating for proper pushbutton operation. We recommend only ever driving this pin low or leaving it floating; <u>this pin should never be driven high while the slide switch is in the “On” position.</u>

5 V and 3.3 V regulators

VSW supplies power to a 5 V regulator, whose output is designated **VREG**. The battery voltage is regulated to 5 V by an MP4423H switching buck converter; although the regulator itself works with input voltages up to 36 V, the motor drivers limit the control board's maximum input voltage to 10.8 V. When available, VREG is generally used to supply logic power for the ATmega32U4, motor drivers, and encoders. The rest of the regulator's achievable output current, which depends on input voltage and ambient conditions, can be used to power other devices; this can include an attached Raspberry Pi (which typically draws a few hundred milliamps). Under typical conditions, up to 2 A of current is available from the VREG output. (We also make a **standalone regulator** [<https://www.pololu.com/product/>]

2858] based on this integrated circuit.)

The MP4423H regulator features an open-drain power good output, **PG**, which requires an external pull-up. PG drives low when the 5 V regulator's output voltage falls below around 85% of the nominal voltage and becomes high-impedance when the output voltage rises above around 90%. The regulator circuit on the Balboa 32U4 control board can be disabled by driving the regulator shutdown pin, **REGSHDN**, high; this will cause 5 V logic power for the control board to be sourced from USB instead if it is available.

The Balboa 32U4 control board also contains a 3.3 V LDO that draws its power from the output of the logic power selection circuit described below. The output of the 3.3 V regulator is designated **3V3** and is used to supply the on-board inertial sensors and level shifters.

Logic power selection

The Balboa 32U4 control board's power selection circuit uses the **TPS2113A power multiplexer** [<https://www.pololu.com/product/2596>] from Texas Instruments to choose whether its 5 V supply (designated **5V**) is sourced from USB or the batteries via the 5 V regulator, enabling the control board to safely and seamlessly transition between them. The TPS2113A is configured to select regulated battery power (VREG) unless the regulator output falls below about 4.5 V. If this happens, it will select the higher of the two sources, which will typically be the USB 5 V bus voltage if the control board is connected to USB.

Consequently, when Balboa 32U4 is connected to a computer via USB, it will receive 5 V logic power even when the power switch is off. This can be useful if you want to upload or test a program without drawing power from the batteries and without operating the motors. It is safe to have USB connected and battery power switched on at the same time.

The currently selected source is indicated by the **STAT** pin; this pin is an open-drain output that is low if the external power source is selected and high-impedance if the USB supply is selected. The current limit of the TPS2113A is set to about 1.9 A nominally. For more information about the power multiplexer, see the **TPS2113A datasheet** [<https://www.pololu.com/file/0J771/tps2113a.pdf.redirect>] (1k redirect).

The 5 V output of the selection circuit is used to supply the control board's ATmega32U4 microcontroller, logic power for the DRV8838 motor drivers, and the encoders; it also optionally powers an attached Raspberry Pi.

Raspberry Pi power

By default, the control board will provide power from its 5V line to an attached Raspberry Pi. In this situation, we recommend switching on the power circuit so that the Raspberry Pi receives power from the batteries through the control board's on-board switching regulator. Alternatively, you can use

a **USB wall power adapter** [<https://www.pololu.com/product/1459>] to supply power through the control board's USB connector, although we have sometimes observed AVR brown-out resets occurring when a board powers the Raspberry Pi this way. A typical computer USB port might not be able to supply enough current to properly power the Balboa 32U4 control board and an attached Raspberry Pi.

Power provided to the Raspberry Pi can be switched off by driving the Raspberry Pi shutdown pin, **RPISHDN**, to 5 V.

An ideal diode circuit on the control board prevents reverse current from flowing into the Balboa 32U4 control board's 5 V supply if the Raspberry Pi is separately powered (for example, through its USB power receptacle). However, starting with the Raspberry Pi 3 Model B+, there is no corresponding ideal diode circuit on the Raspberry Pi's USB power input, so it is possible for the control board to backfeed a USB power adapter through the Raspberry Pi. As a result, we do not recommend connecting external USB power to the Raspberry Pi while it is powered through the control board.

Backfeeding is not an issue with older Raspberry Pi versions, which do have a diode circuit on the USB power input. With Raspberry Pi versions prior to the Pi 3 B+, it is safe to have any combination of control board USB power, battery power, and Raspberry Pi USB power connected to the system.

Note that the diode circuit prevents power from being shared in the reverse direction: the Raspberry Pi cannot supply 5 V logic power to the control board through the 40-pin connector.

Power distribution

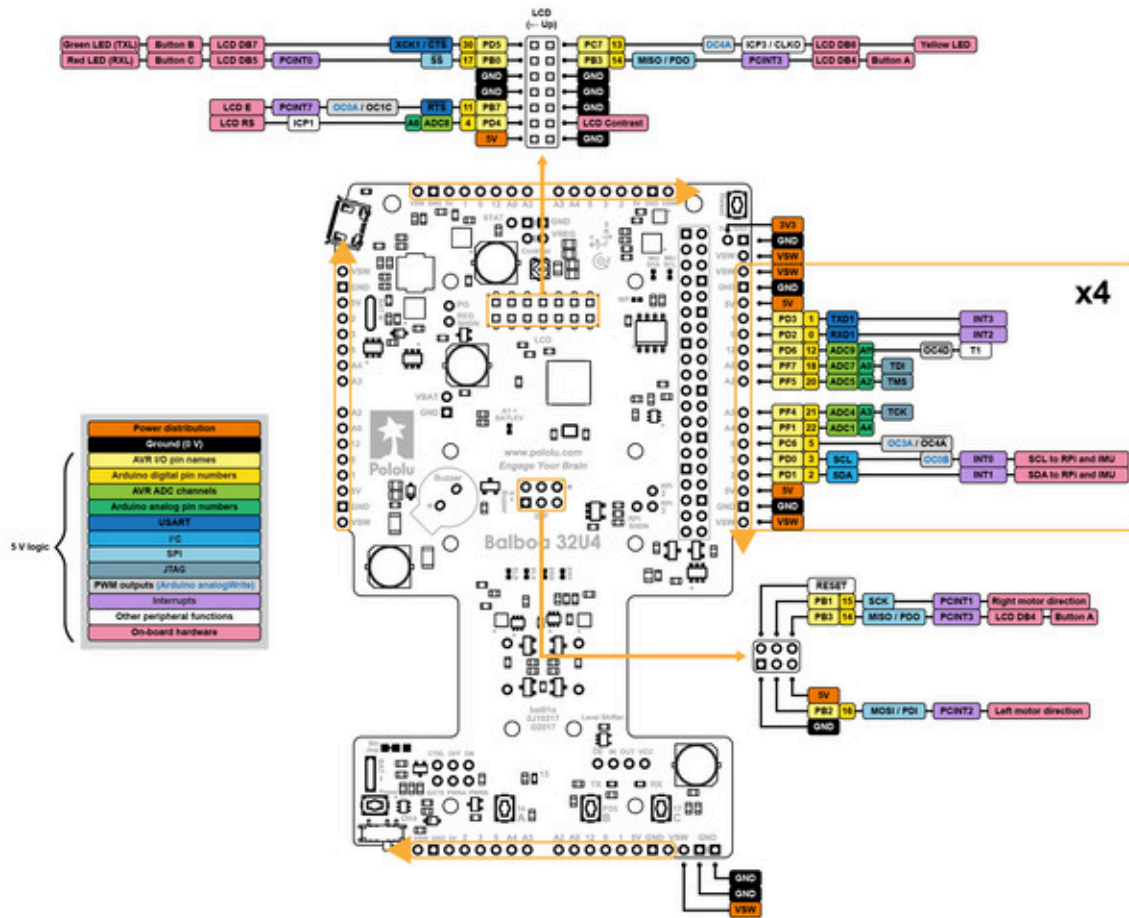
- **VBAT** is connected to the battery contact labeled **BAT+** and provides a direct connection to the battery supply.
- **VSW** is the battery voltage after reverse-voltage protection and the power switch circuit.
- **VREG** is the output of the on-board 5 V regulator.
- **5V** is the output of the TPS2113A power multiplexer circuit which is connected to VREG by default, but switches to 5 V USB power if VREG is too low.
- **3V3** is the output of the 3.3 V LDO regulator.

See **Section 3.7** for a diagram of the board's power access points.

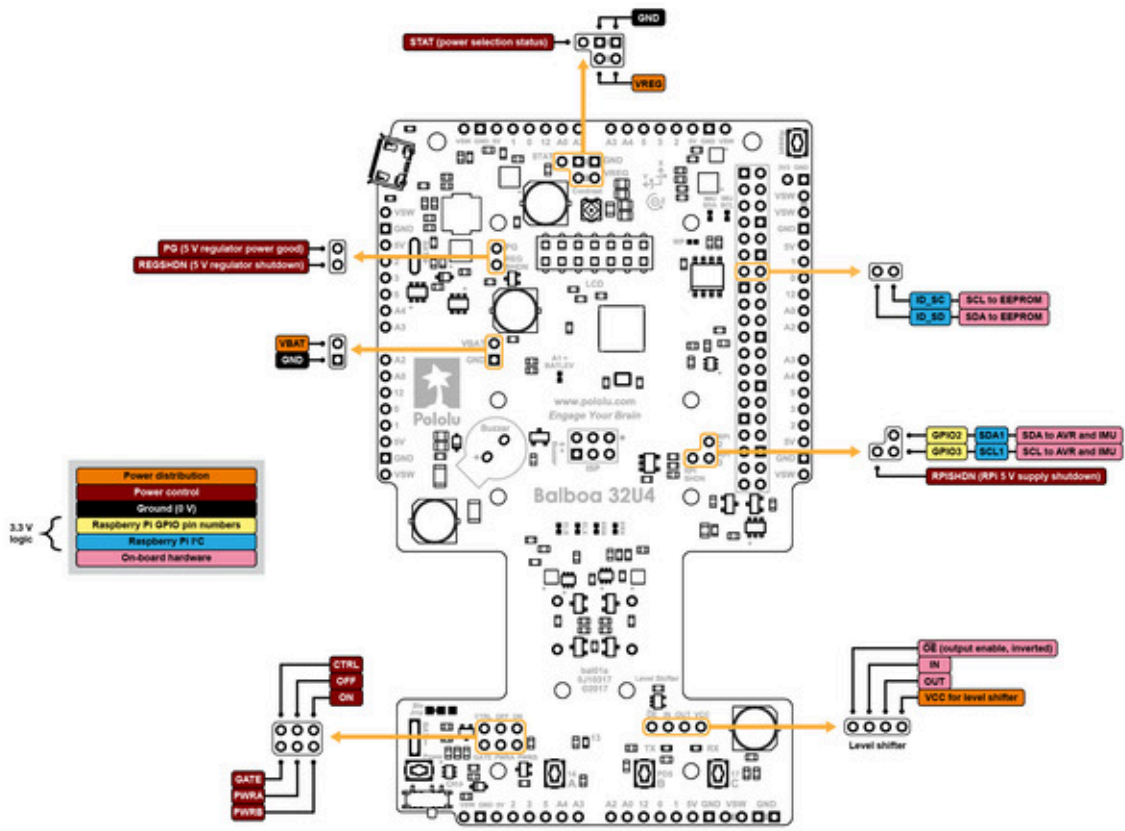
3.7. Expansion headers

The Balboa 32U4 control board has expansion headers on its four edges that break out several free general-purpose I/O lines from the ATmega32U4 microcontroller along with a few power pins. Various power inputs, outputs, and control pins are also accessible elsewhere on the board. The following diagrams identify the locations of these pins and the hardware associated with them; they are also available as a **printable PDF** [<https://www.pololu.com/file/0J1268/balboa-32u4-control-board-pinout->

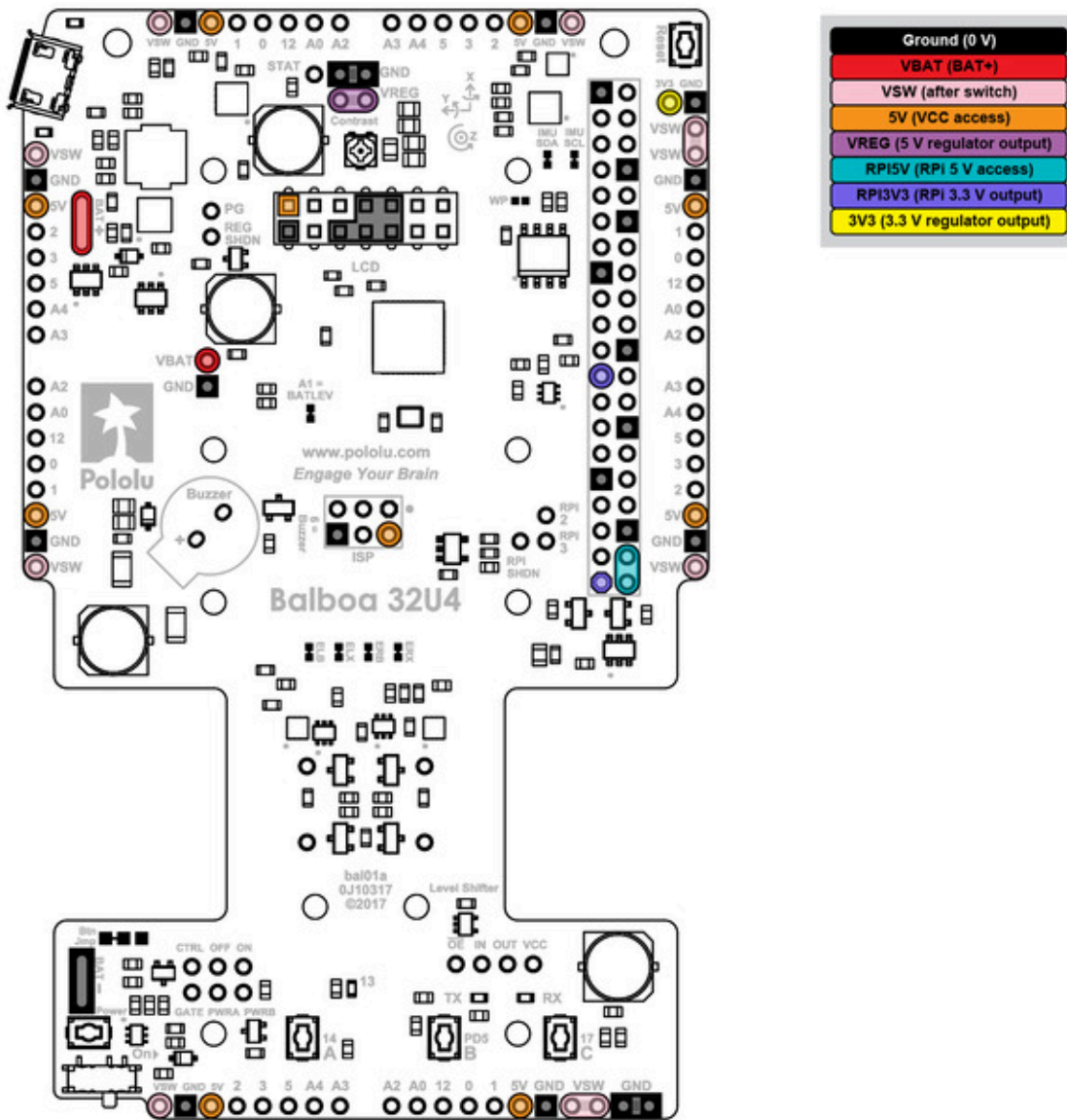
[power.pdf](#)] (2MB pdf). For more information about the ATmega32U4 microcontroller and its peripherals, see Atmel's ATmega32U4 documentation.



Pinout diagram of the Balboa 32U4 control board (ATmega32U4 pinout and peripherals).



Pinout diagram of the Balboa 32U4 control board (Raspberry Pi pinout and peripherals, level shifter, and board power control).



Power distribution diagram of the Balboa 32U4 control board.

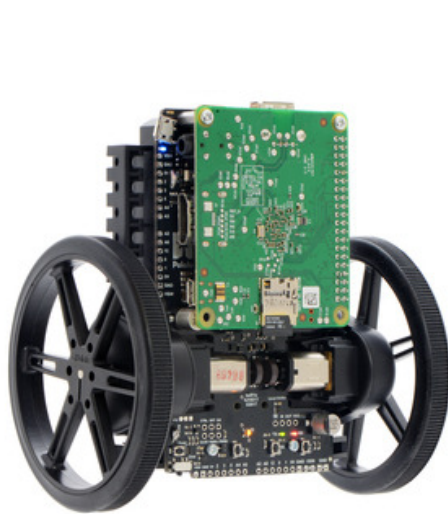
3.8. Raspberry Pi interface and level shifters

The Balboa 32U4 control board was designed to be easy to interface with a Raspberry Pi single-board computer to expand Balboa’s processing power. The board has mounting locations for a connector and two standoffs, matching part of the Raspberry Pi HAT (Hardware Attached on Top) specification, and it is designed to connect to the Model B+ and newer versions of the Raspberry Pi with 40-pin GPIO headers (including the **Raspberry Pi 3 Model B** [<https://www.pololu.com/product/2759>] and **Model A+** [<https://www.pololu.com/product/2760>]).

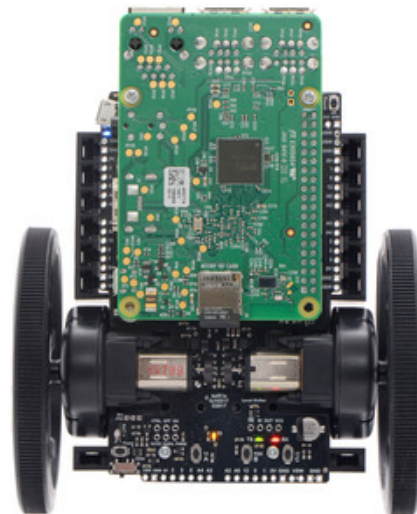


The Balboa 32U4 kit does not include a Raspberry Pi connector or mounting hardware. To add a Raspberry Pi, you will need a **2×20-pin 0.1" female header** [<https://www.pololu.com/product/1037>] and a set of two **standoffs** [<https://www.pololu.com/product/2713>], **screws** [<https://www.pololu.com/product/1968>], and **nuts** [<https://www.pololu.com/product/1967>].

Note that the Balboa is intended to be used with our **standoffs with 4 mm threads** [<https://www.pololu.com/product/2713>]. Our standoffs with longer (6 mm) threads will interfere with the chassis.



Balboa 32U4 Balancing Robot with 80×10mm wheels and a Raspberry Pi 1 Model A+.



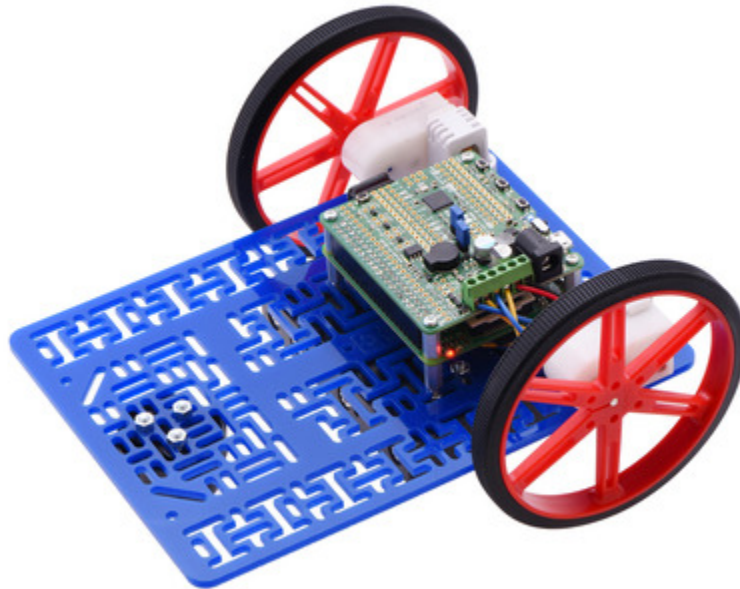
Balboa 32U4 Balancing Robot with 80×10mm wheels and a Raspberry Pi 3 Model B.

I²C communication

When used with a Raspberry Pi, the control board is designed to serve as an auxiliary controller, communicating with the Raspberry Pi using an I²C interface (also known as 2-wire Serial Interface, or TWI). As such, the ATmega32U4 microcontroller's I²C data and clock lines (SDA and SCL) are connected to the corresponding lines on the Raspberry Pi's I²C bus 1 through on-board level-shifting circuits. These bidirectional level shifters convert between the AVR's 5 V logic level and the Raspberry Pi's 3.3 V logic level.

We have written an **Arduino library** [<https://github.com/pololu/pololu-rpi-slave-arduino-library>] for our our 32U4 family of boards that lets them act as an I²C slave and provides a framework for communication between the ATmega32U4 and a Raspberry Pi master.

A **tutorial** [<https://www.pololu.com/blog/577>] on the Pololu blog demonstrates this library and its included example code, using them to make a robot that can be remotely controlled and monitored through a web server running on the Raspberry Pi. This tutorial uses our **A-Star 32U4 Robot Controller SV** [<https://www.pololu.com/product/3119>] and a laser cut chassis, but the instructions for setting up your Raspberry Pi and Raspberry Pi slave library for Arduino still apply for the Balboa 32U4, and we will be releasing an updated tutorial with steps specific to the Balboa soon.

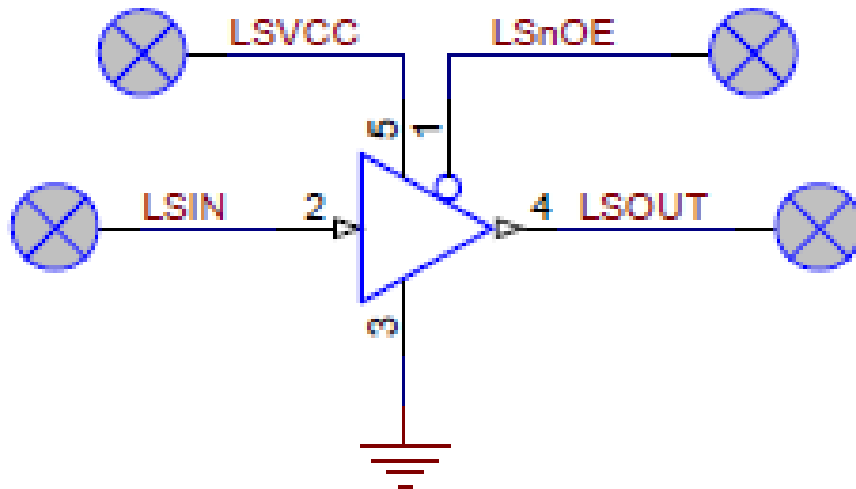


Raspberry Pi robot using the A-Star 32U4 Robot Controller.

General-purpose level shifter

In addition to the dedicated I²C level shifters, the board also makes available a single-channel, tristatable, unidirectional level shifter that is not connected to any signals by default. Four pins are exposed: $\overline{\text{OE}}$ (output enable), **IN** (input), **OUT** (shifted output), and **VCC** (logic supply voltage).

- When $\overline{\text{OE}}$ is high, OUT is in a high impedance state.
- When $\overline{\text{OE}}$ is low, OUT matches the state of **IN**, shifted to the voltage supplied on VCC.



For example, if you pull $\overline{\text{OE}}$ low, connect a 3.3 V signal to IN, and connect 5V to VCC, the signal will be shifted to 5 V logic level on OUT.

The input logic level can be 1.8 V to 5.5 V, while VCC (and the output logic level) can be 3 V to 5.5 V. The IN signal can have either a lower or higher logic level than the VCC voltage: you could connect a 5 V signal to IN and a 3.3 V to VCC or a 3.3 V signal to IN and a 5 V to VCC.

Powering the Raspberry Pi from the control board

The control board will provide 5 V power to an attached Raspberry Pi by default. See **Section 3.6** for more details about how power is shared and can be controlled between the two boards.

ID EEPROM

The Balboa 32U4 control board includes a 32-kilobit (4096-byte) EEPROM that connects to the Raspberry Pi's ID_SD and ID_SC pins. The EEPROM ships with its contents blank, but you can program it as an ID EEPROM in the format specified by the **Raspberry Pi HAT specifications** [<https://github.com/raspberrypi/hats>], using the utilities provided there. When suitably programmed, the EEPROM can help the Raspberry Pi identify and configure itself to work with the Balboa 32U4 control board.

Write protection for the EEPROM can be enabled by using solder to bridge the surface-mount jumper

labeled “WP” next to the EEPROM chip. (The EEPROM is not write-protected by default.)

3.9. Pin assignments

The table below lists the most important pin assignments for the ATmega32U4 on the Balboa 32U4 control board. This table is helpful if you want to add your own electronics to Balboa 32U4, write your own low-level code for interfacing with the hardware, or just want to understand better how Balboa32U4 works. Each row represents a physical pin on the ATmega32U4.

The “ATmega32U4 pin name” column shows the official name of the pin according to the **ATmega32U4 datasheet** [<https://www.microchip.com/en-us/product/ATmega32u4>].

The “Arduino pin names” column lists the names provided by the Arduino environment for the pin. These names can generally be used as arguments to any function that takes a pin number. However, there are some exceptions. For example, passing the number 4 to `analogRead` actually reads pin A4, not pin 4. Also, due to hardware limitations, some functions only work on a limited set of pins.

The “Balboa 32U4 functions” column documents what the pin is used for on the Balboa 32U4 control board. Many pins can serve multiple purposes concurrently by switching modes. For example, PB0 can read the state of button C when it is an input, and it can control the red LED and serve as an LCD data line when it is an output.

The “Note/alternate functions” column documents other features of the pin, although some of those features might be impractical to use.

ATmega32U4 pin name	Arduino pin names	Balboa 32U4 control board functions	Notes/alternate functions
PB7	11	LCD control line (E)	Timer0 PWM output A (OC0A) Timer1 PWM output C (OC1C) UART flow control ($\overline{\text{RTS}}$) Pin-change interrupt (PCINT7)
PD4	4, A6, 24	LCD control line (RS)	Analog input (ADC8) Timer1 input capture pin (ICP1)
PB3	14, MISO	User pushbutton A LCD data line DB4	SPI Master Input/Slave Output (MISO) Pin-change interrupt (PCINT3) ISP programming line (PDO)
PB0	17, LED_BUILTIN_RX, SS	Red LED (RX) User pushbutton C LCD data line DB5	SPI slave select ($\overline{\text{SS}}$) Pin-change interrupt (PCINT0)
PC7	13, LED_BUILTIN	Yellow LED LCD data line DB6	Timer4 PWM output A (OC4A) Timer3 input capture pin (ICP3) Divided system clock output (CLKO)
PD5	30, LED_BUILTIN_TX	Green LED (TX) User pushbutton B LCD data line DB7	UART external clock (XCK1) UART flow control ($\overline{\text{CTS}}$)
PD7	6, A7, 25	Buzzer PWM	Analog input (ADC10) Timer4 PWM output D (OC4D) Timer0 counter source (T0)
PF6	A1, 19	Battery level input (VIN/3)	Analog input (ADC6) JTAG test data out (TDO)
PB6	10, A10, 28	Left Motor PWM	Analog input (ADC13)

ATmega32U4 pin name	Arduino pin names	Balboa 32U4 control board functions	Notes/alternate functions
			Timer1 PWM output B (OC1B) Timer4 PWM output B (OC4B) Pin-change interrupt (PCINT6) SPI Master Output/Slave Input (MOSI)
PB2	16, MOSI	Left motor direction	Pin-change interrupt (PCINT2) ISP programming line (PDI)
PB5	9, A9, 27	Right motor PWM	Analog input (ADC12) Timer1 PWM output A (OC1A) Timer4 PWM output B ($\overline{OC4B}$) Pin-change interrupt (PCINT5)
PB1	15, SCK	Right motor direction	SPI Clock (SCK) Pin-change interrupt (PCINT1) ISP programming line (SCK)
PB4	8, A8, 26	Left encoder XORed input	Analog input (ADC11) Pin-change interrupt (PCINT4)
PE2	-	Left encoder input	Hardware bootloader select (\overline{HWPB})
PE6	7	Right encoder XORed input	Analog comparator negative input (AIN0) External interrupt source (INT6)
PF0	A5, 23	Right encoder input	Analog input (ADC0)
PD0	3, SCL	I ² C clock for Raspberry Pi communication and inertial sensors	Timer0 PWM output B (OC0B)

ATmega32U4 pin name	Arduino pin names	Balboa 32U4 control board functions	Notes/alternate functions
			External interrupt source ($\overline{\text{INT0}}$)
PD1	2, SDA	I ² C data for Raspberry Pi communication and inertial sensors	External interrupt source ($\overline{\text{INT1}}$)
PD2	0	<i>Free I/O</i>	UART receive pin (RXD1) External interrupt source ($\overline{\text{INT2}}$)
PD3	1	<i>Free I/O</i>	UART transmit pin (TXD1) External interrupt source ($\overline{\text{INT3}}$)
PC6	5	<i>Free I/O</i>	Timer3 PWM output A (OC3A) Timer4 PWM output A ($\overline{\text{OC4A}}$)
PD6	12, A11, 29	<i>Free I/O</i>	Analog input (ADC9) Timer4 PWM output D ($\overline{\text{OC4D}}$) Timer1 counter source (T1)
PF7	A0, 18	<i>Free I/O</i>	Analog input (ADC7) JTAG test data in (TDI)
PF5	A2, 20	<i>Free I/O</i>	Analog input (ADC5) JTAG test mode select (TMS)
PF4	A3, 21	<i>Free I/O</i>	Analog input (ADC4) JTAG test clock (TCK)
PF1	A4, 22	<i>Free I/O</i>	Analog input (ADC1)
$\overline{\text{RESET}}$	-	Reset pushbutton	internally pulled high, active low
AREF	-	-	Analog reference

3.10. Adding electronics

This section gives tips for how additional electronics can be connected to the Balboa 32U4 control board.

Free I/O pins

If you want your additional devices to send or receive information from the AVR, you will need to connect them to one or more of the AVR's I/O pins. The pin assignment table in **Section 3.9** lists all of these pins and how they are used. Many of the I/O pins are already being used for some other purpose on the board, but there are 8 free I/O pins: 0, 1, 5, 12, A0, A2, A3, and A4 (accessible on the expansion headers on the four edges of the board, along with pins 2 and 3). Any of the free I/O lines can be used as basic digital inputs or outputs; each pin also has some special capabilities.

Pin 0 (PD2) and pin 1 (PD3) are the RX and TX lines of the AVR's TTL serial port.

Pin 5 (PC6) is a hardware PWM output and is usable with the Arduino `analogWrite()` function. Pin 12 (A11/PD6) can also be used as a PWM output, but it is not supported by `analogWrite()`, and using pin 12 for PWM might conflict with uses of pin 6 (which controls the buzzer by default) as these two pins are complementary outputs of Timer4 channel D.

Pins 12 (A11/PD6), A0 (18/PF7), A2 (20/PF5), A3 (21/PF4), and A4 (22/PF1) can be used as analog inputs.

Freeing up more I/O pins

If you are not using an LCD on Balboa and the free I/O pins are not sufficient for connecting the devices you want to connect, you can gain access to a few more I/O pins on the LCD connector.

With no LCD, pin 11 (PB7) and pin 4 (A6/PD4) are free. Both pins can be used for digital input and output. In addition, pin 11 can be used as a PWM output and a pin change interrupt and pin 4 can be used as an analog input.

If you do not have an LCD connected, you can use the LCD contrast potentiometer for other purposes. The output of the potentiometer is a 0 V to 5 V signal which is accessible on the LCD connector. It can be connected to any free analog input if you want to read it from the AVR, or it might be useful to connect it to the other electronics that you are adding.

Be careful about connecting electronics to pin 13 (PC7), pin 17 (PB0), and pin 30 (PD5) on the LCD connector. These pins are used to control the LEDs on Balboa 32U4. All three of these pins are controlled as outputs by the bootloader. Pin 17 (PB0) and pin 30 (PD5) are used as RX and TX indicators, so if you are sending or receiving data over USB then the Arduino USB code will drive those pins in its interrupt service routines while your sketch is running.

I²C devices

It should be possible to attach additional I²C slave devices to the control board's I²C bus as long as the additional devices' slave addresses do not conflict with those of the inertial sensors. The LSM6DS33

uses 7-bit address 1101011, while the LIS3MDL uses 7-bit address 0011110. The ATmega32U4's I²C pins (2 and 3) operate at 5 V. If you are connecting a 3.3 V device, you can connect it to the 3.3 V side of the bus instead (accessible through [Raspberry Pi GPIO pins](#) 2, for SDA, and 3, for SCL, even if a Raspberry Pi is not connected). Separate level shifters might be necessary to interface with devices that use other voltages.

If you do not want to use the inertial sensors on the I²C bus, you can cut the surface-mount jumpers labeled “IMU SDA Jmp” and “IMU SCL Jmp”. (Note that this will remove Balboa's ability to balance!) This frees up pin 2 (PD1) and pin 3 (PD0) for limited use as digital inputs and outputs as long as a Raspberry Pi is not attached to the control board. Note that the AVR's I²C pins will remain connected to the on-board I²C level shifters and will therefore still be pulled up to 5 V.

Power

The control board's power nodes are accessible in several areas on the board. If you power additional devices from VSW, then they will be powered whenever the control board's power is in ON, and they will receive whatever voltage the batteries are outputting. If you power them from VREG, they will get 5 V power whenever the batteries are installed and the power is on (but they cannot be powered from USB). If you power them from a 5V pin, then they will receive 5V power whenever the control board's logic components are powered. If you power them from 3V3, they will receive 3.3V power whenever the control board's logic components are powered. For more information about these power nodes and how much current they can provide, see **Section 3.6**.

It is also possible to add your own power switch to control power to Balboa 32U4, as described in **Section 3.6**.

Ground

You should make sure that all the grounds in your system are connected. The Balboa 32U4 control board's ground node can be accessed from pins labeled “GND”. It should be connected to the ground node of every other circuit board or device you add to the robot.

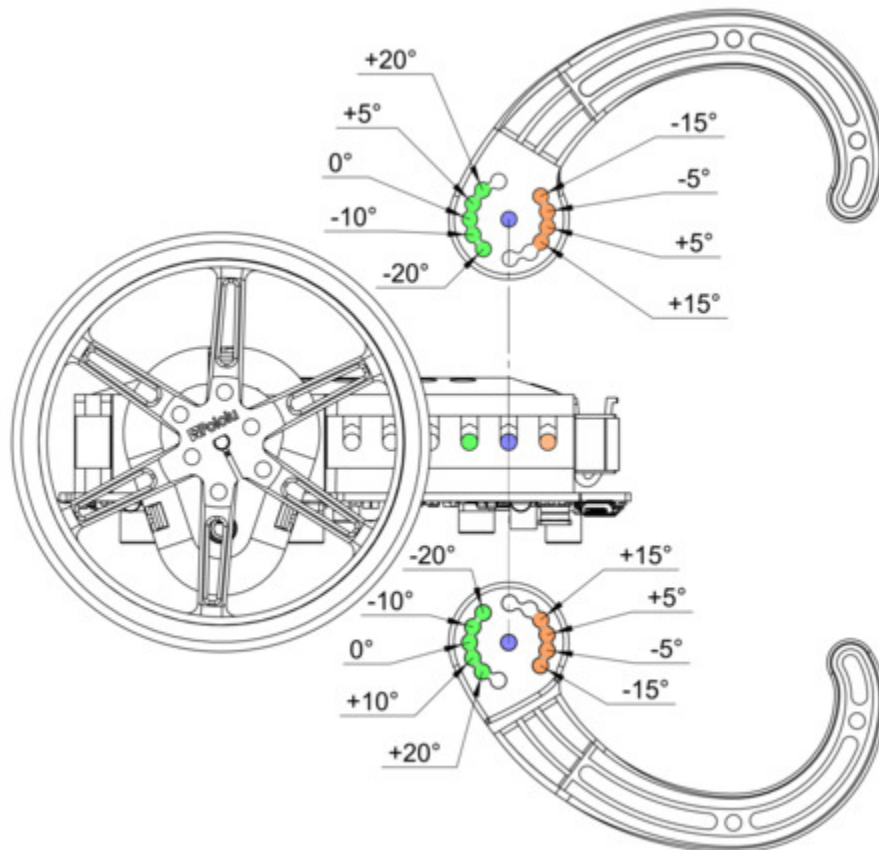
3.11. AVR timers

The ATmega32U4 has 4 timers: Timer0, Timer1, Timer3, and Timer4. Each timer has a different set of features, as documented in the datasheet.

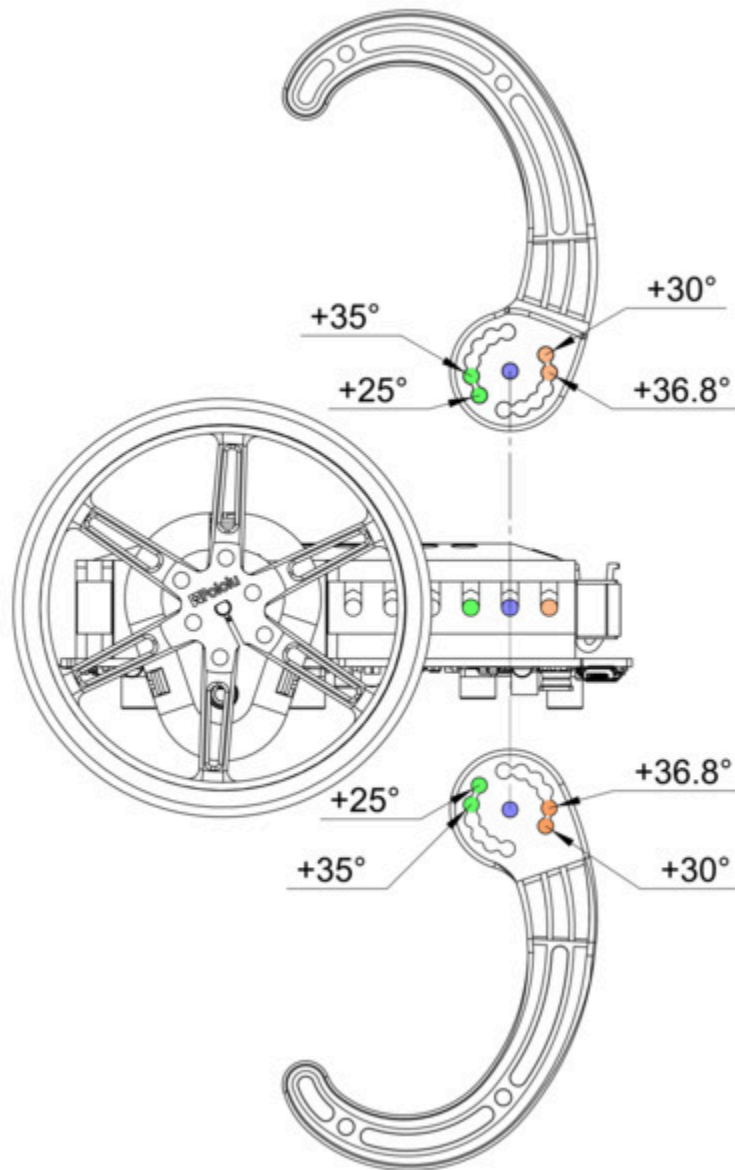
- Timer0 is used by the Arduino environment for timing-related functions like `millis()`.
- Timer1 is used by the Balboa32U4 Arduino library for driving motors.
- Timer3 is *not* used by the Balboa32U4 Arduino library and can be freely used for your own purposes.
- Timer4 is used by the Balboa32U4 Arduino library for controlling the buzzer.

3.12. Bumper cage

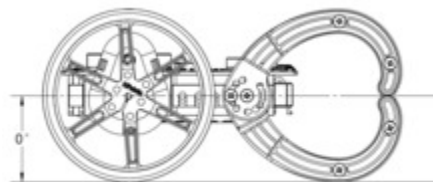
Along with protecting the robot during falls or collisions, the bumper cage can be used to hold the robot in a particular position when not balancing. See the instructions in **Section 4** for details for how to put it together. The diagrams below can be used to help identify which mounting holes to use when assembling the bumper cage to achieve particular angles (with respect to the horizontal). These diagrams all use the 80mm wheel; note that the angles will differ when using different diameter wheels.

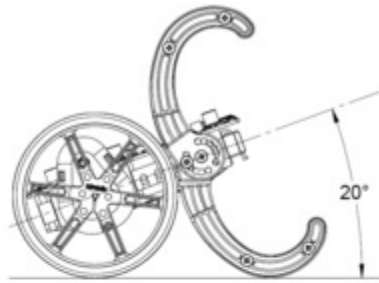


Note that the bumper skids on either side of the robot can be adjusted independently from the other side, allowing for asymmetric configurations. The arms can be flipped to achieve some additional angles as shown below.

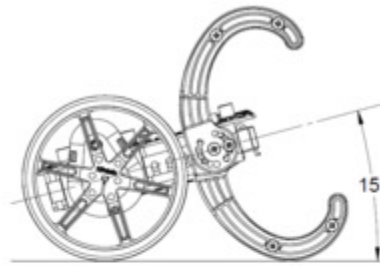


The diagrams below show the bumper cage assembled and installed on the Balboa in various positions; the top pictures show various inclined positions available, while the bottom picture shows the declined positions.

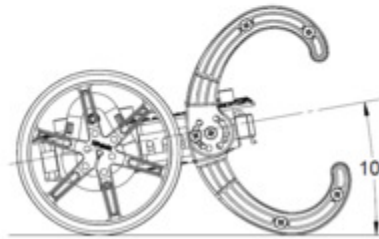




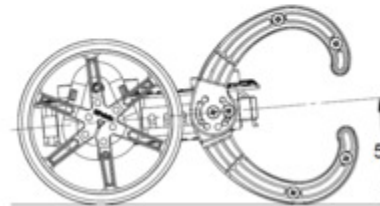
1 20-degree incline



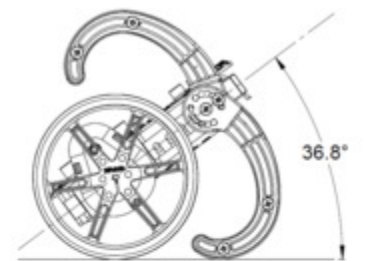
2 15-degree incline



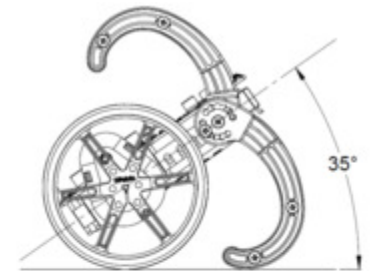
3 10-degree incline



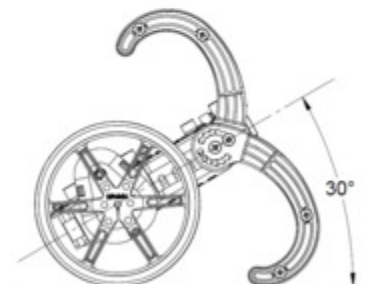
4 5-degree incline



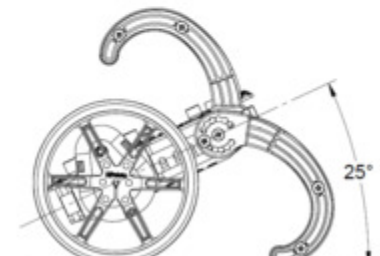
1 36.8-degree incline



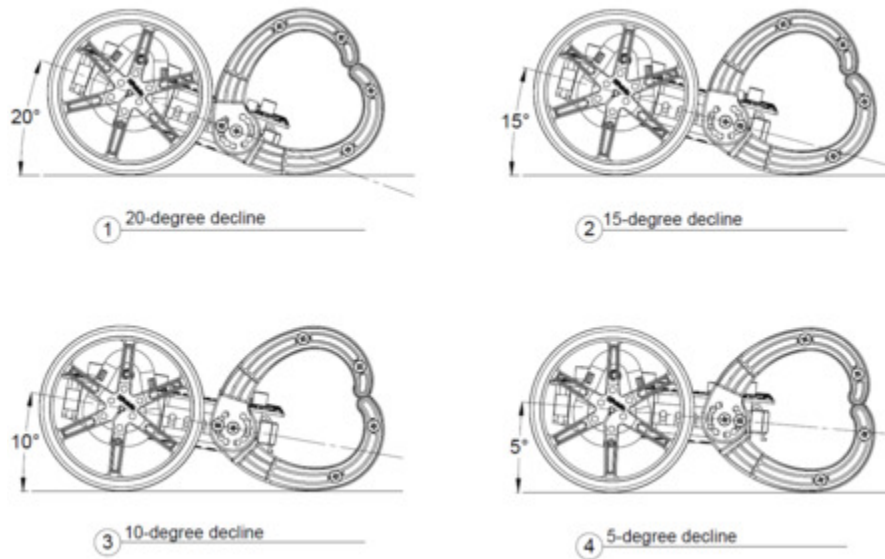
2 35-degree incline



3 30-degree incline

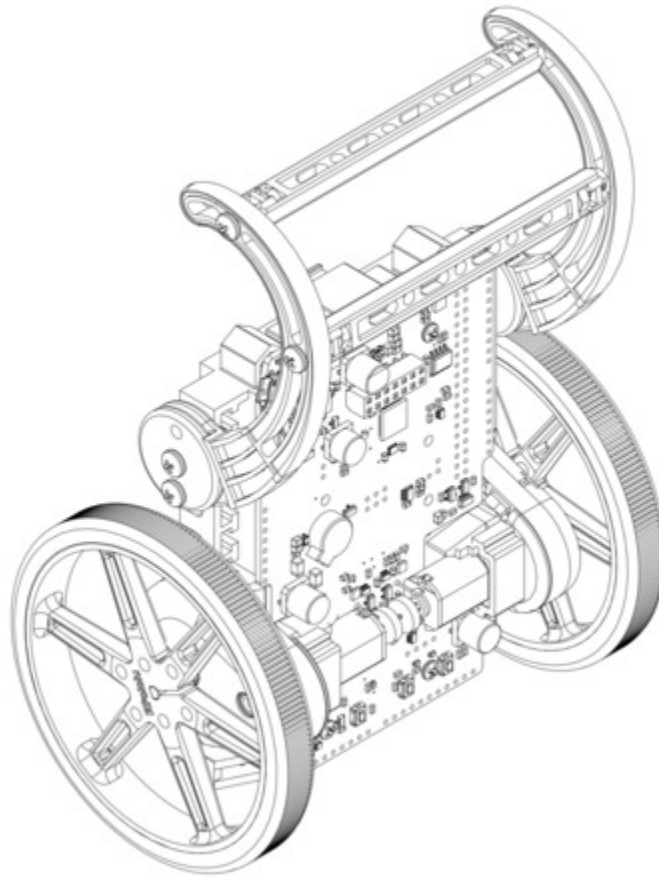


4 25-degree incline



These diagrams are also available in a **downloadable PDF** [<https://www.pololu.com/file/0J1284/cha01-bumper-cage-diagrams.pdf>] (2MB pdf).

Additionally, the included spacers can be used in place of the pair of bumper skids on either side of the robot and allow you to use just one side of the bumper cage.



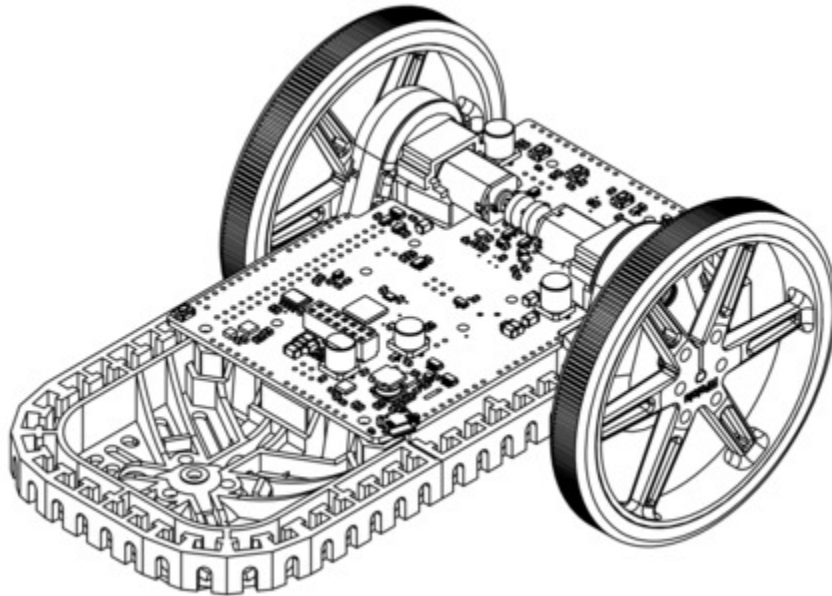
3.13. Stability Conversion Kit

This accessory kit is an add-on extension for the Balboa chassis that provides additional mounting options and support for a ball caster.



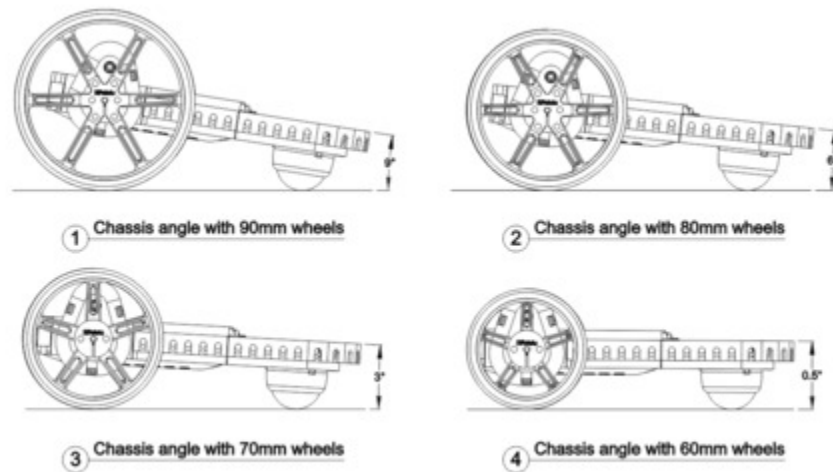
Stability Conversion Kit for Balboa.

When installed on the Balboa chassis, the ball caster on the Stability Conversion Kit provides a smooth third point of contact for traditional differential-drive applications. See **Section 4** for assembly details.



Note that using different diameter wheels on the Balboa with the Stability Conversion Kit produces different decline angles for the robot. The diagrams below show the Stability Conversion Kit

assembled and installed on the Balboa with various wheel sizes.



These diagrams are also available in a **downloadable PDF** [<https://www.pololu.com/file/0J1533/stability-conversion-kit-for-balboa-dimensions.pdf>] (392k pdf).

3.14. Schematics and dimensions

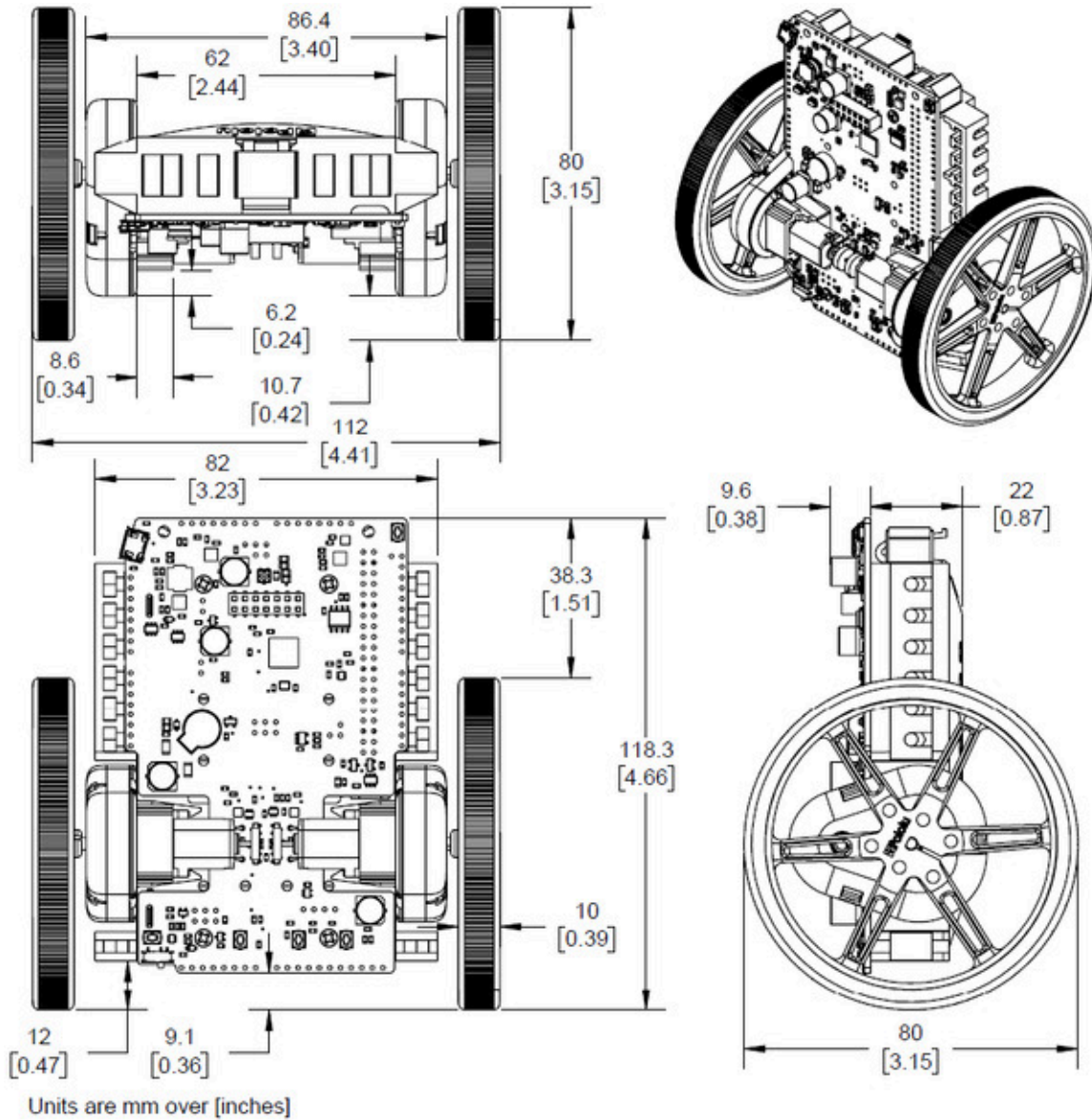
Schematics

The schematic diagram for the Balboa 32U4 control board is available as a PDF: **Balboa 32U4 control board schematic diagram** [<https://www.pololu.com/file/0J1267/balboa-32u4-control-board-schematic.pdf>] (587k pdf).

Dimensions

The following DXF shows the main board outline along with the sizes and locations of all of the holes on the board: **Balboa 32U4 control board drill guide** [<https://www.pololu.com/file/0J1265/bal01a-drill.dxf>] (285k dxf).

The following picture shows the approximate dimensions of the assembled Balboa 32U4 robot:



Dimensions of the Balboa 32U4 Balancing Robot with 80×10mm wheels.

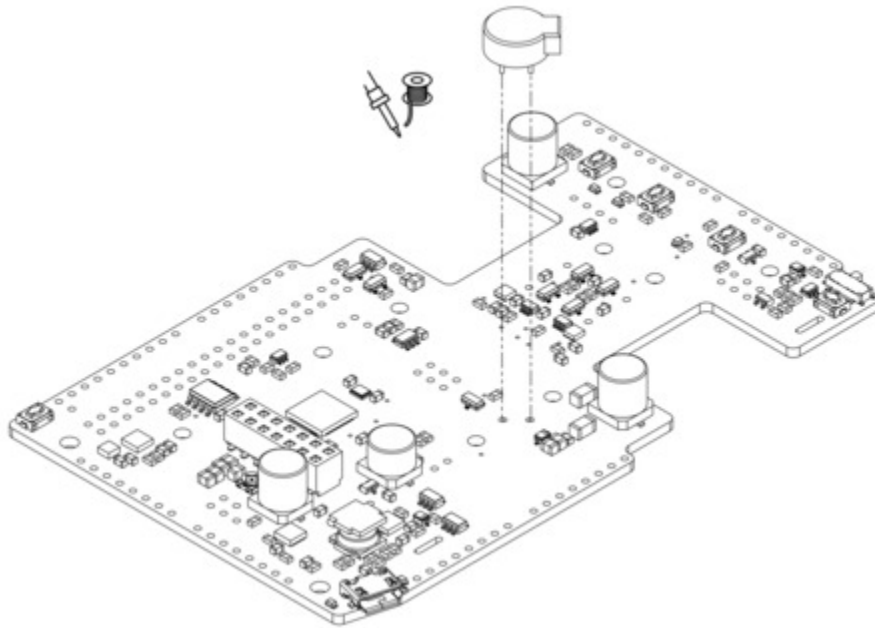
4. Assembling the Balboa 32U4 kit



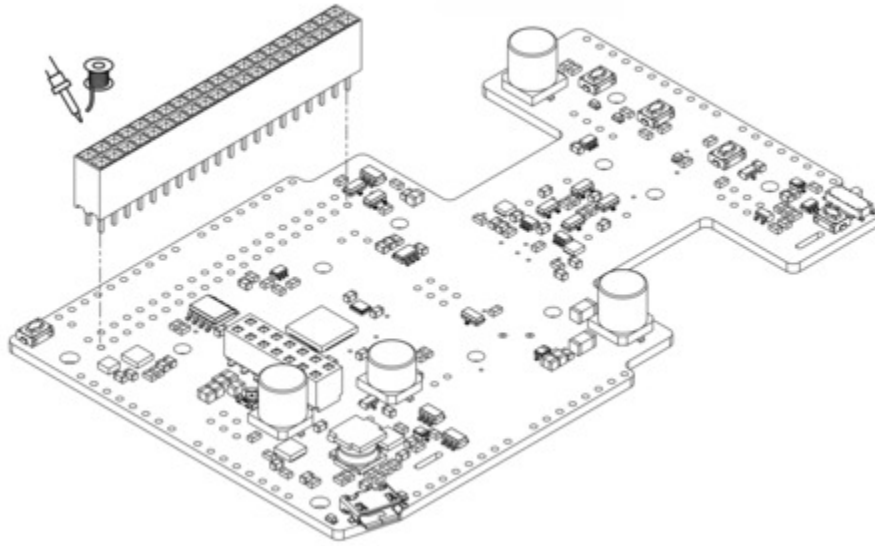
See **Section 1.1** for a diagram to help you identify the contents of the Balboa 32U4 robot kit.

Preparing electronics

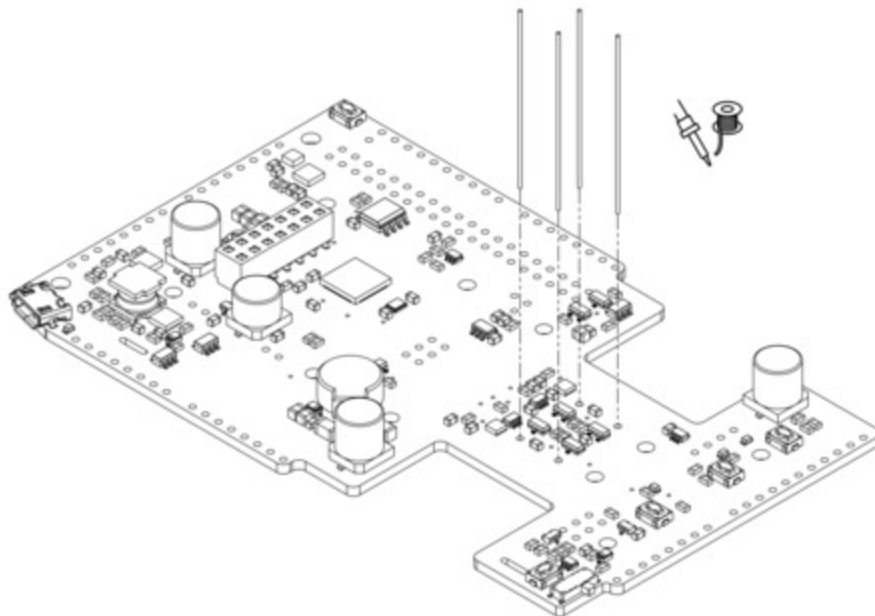
1. Before doing any assembly, now is a good time to solder in the buzzer to the Balboa 32U4 control board.



2. **Optional:** This is a convenient time to add any other optional electronics or headers (such as a **2×20 female header** [<https://www.pololu.com/product/1037>] for mounting a Raspberry Pi).



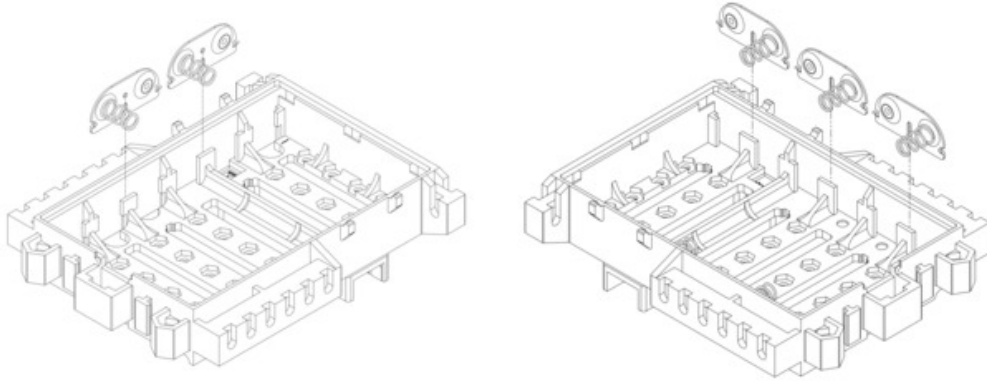
3. Cut two of the included jumper wires in half and solder them to the motor output pins with the excess wire protruding out of the top of the board as shown.



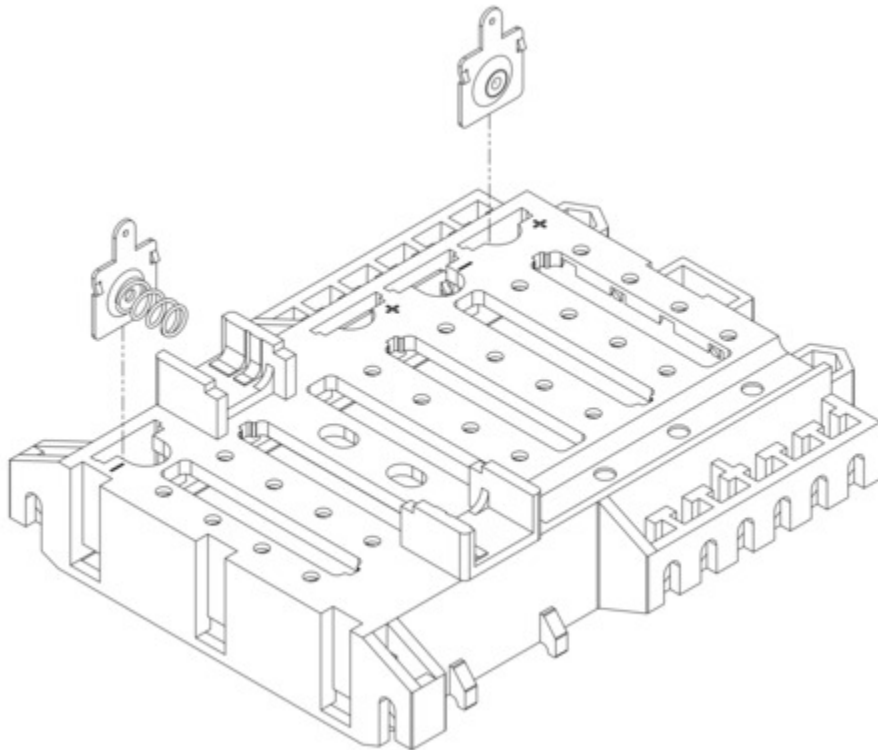
Battery contacts and electronics

4. Set aside the Balboa 32U4 control board and insert the double-sided battery contacts as shown below.

Note: there are two different kinds of double-sided battery contacts, one with the spring on the left and one with the spring on the right, and they must be installed in the correct locations to make proper contact with the batteries.

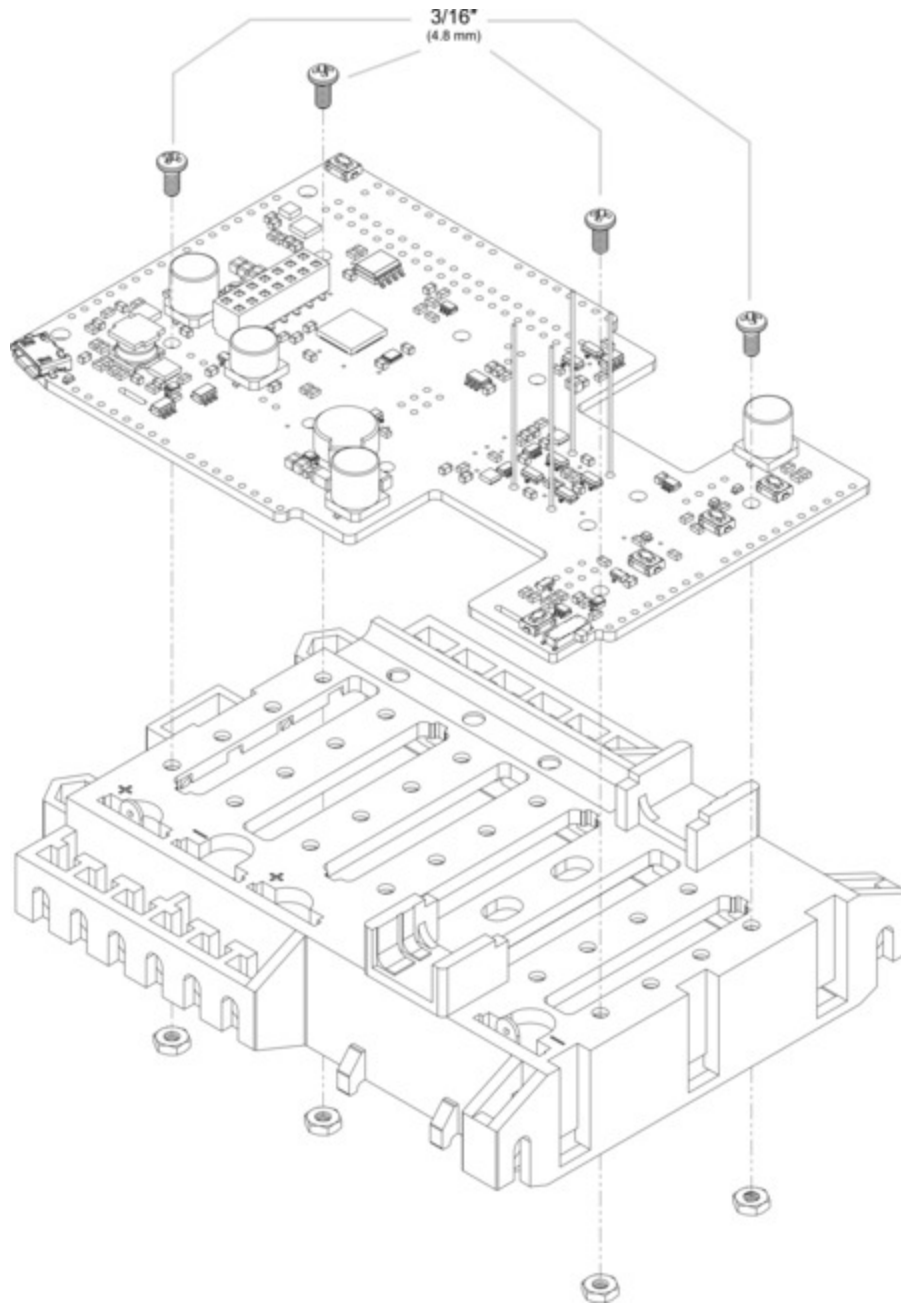


5. Flip the chassis over and insert the two individual battery contact terminals into the top of the chassis.

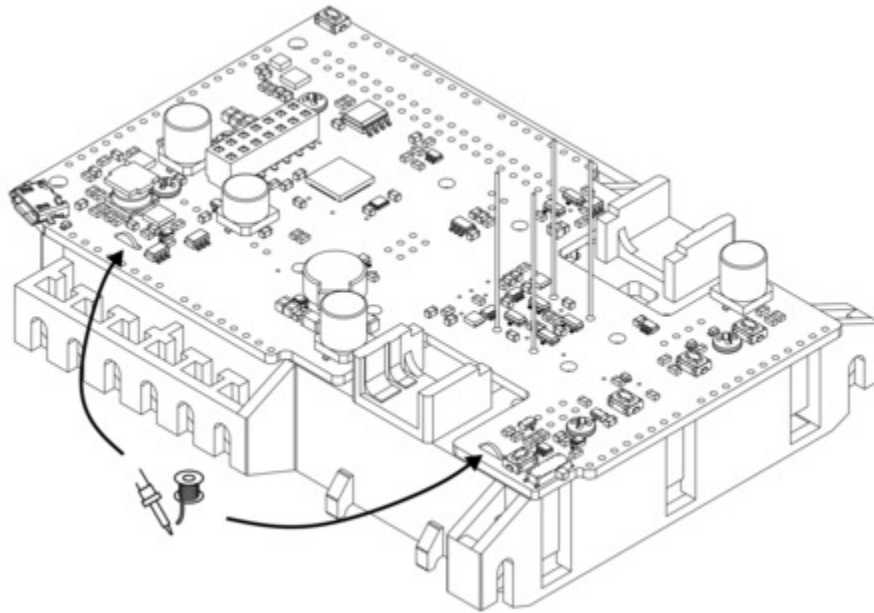


6. Place the Balboa 32U4 control board on the chassis, making sure the battery terminals insert into the slots on the board. Secure the board in place using the four included #2-56 screws

and nuts.

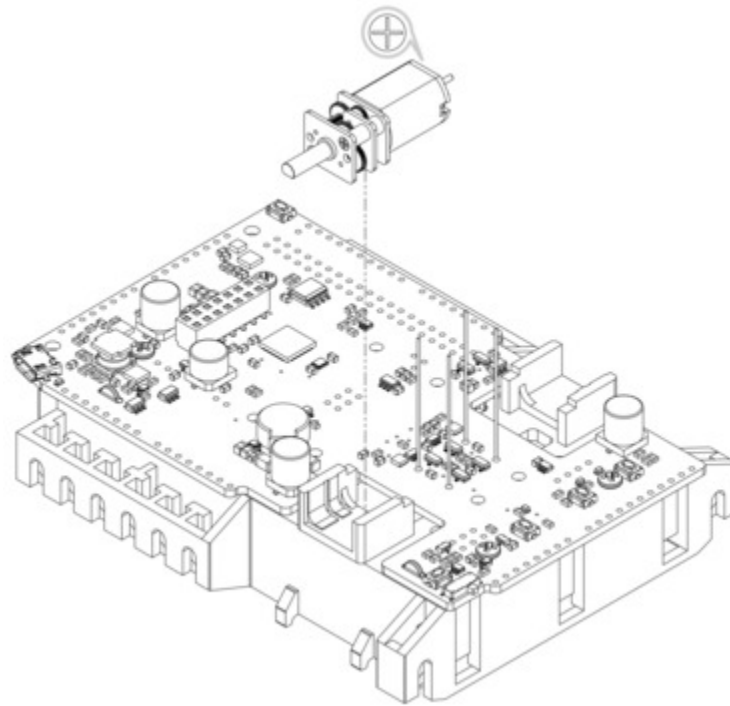


7. Solder the battery terminals to the Balboa 32U4 control board.

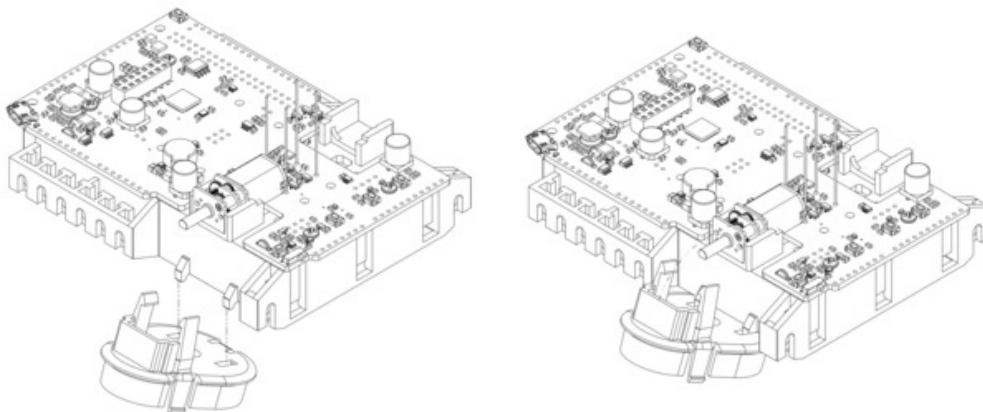


Motors and encoders

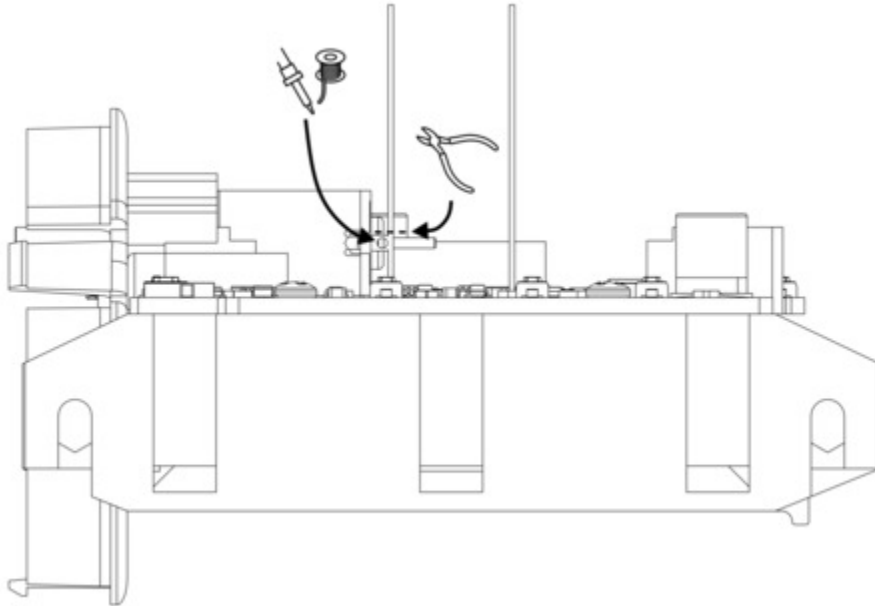
8. Place a motor into one of the motor slots on the chassis with its positive terminal toward the longer end of the board, as indicated. (When the Balboa is fully assembled and balancing upright, the positive motor terminal should be closer to the top.) When properly seated in the slot, the face plate of the motor gearbox will be flush with the edge of the slot.



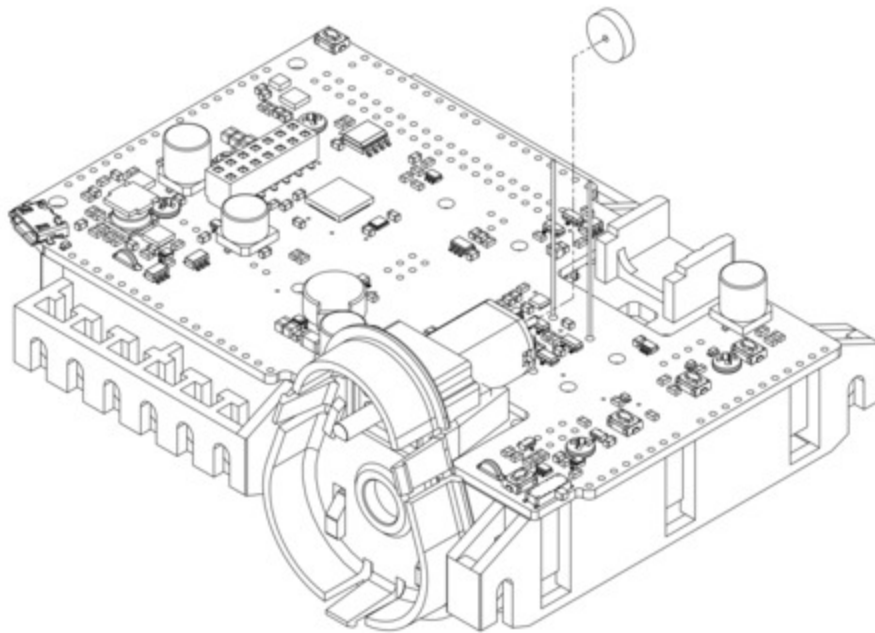
9. Install the motor retention clip/gearbox housing by aligning the two tabs on the chassis with the slots on the clip, sliding the clip up until the tabs are seated in the slots, and rotating the clip into position until you hear it click into place.



10. Clip the motor wires to an appropriate length and solder them to the motor terminals.



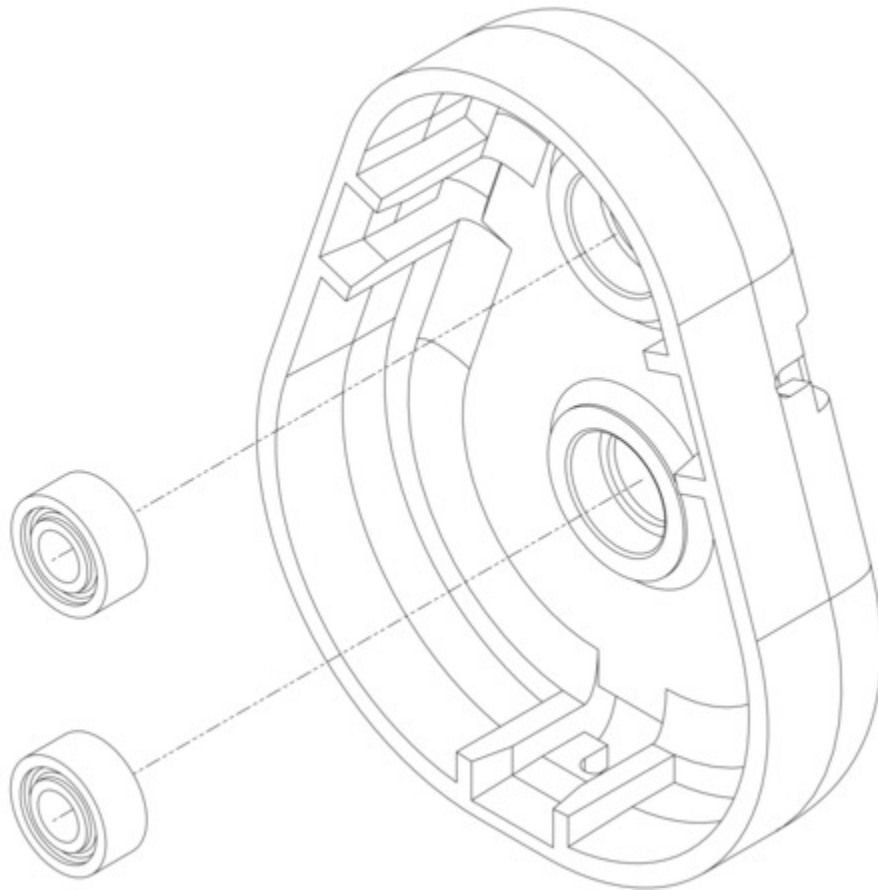
11. Install the magnetic encoder disc on the motor's extended motor shaft. It should be flush with the end of the shaft and align with the sensors on the Balboa 32U4 control board.



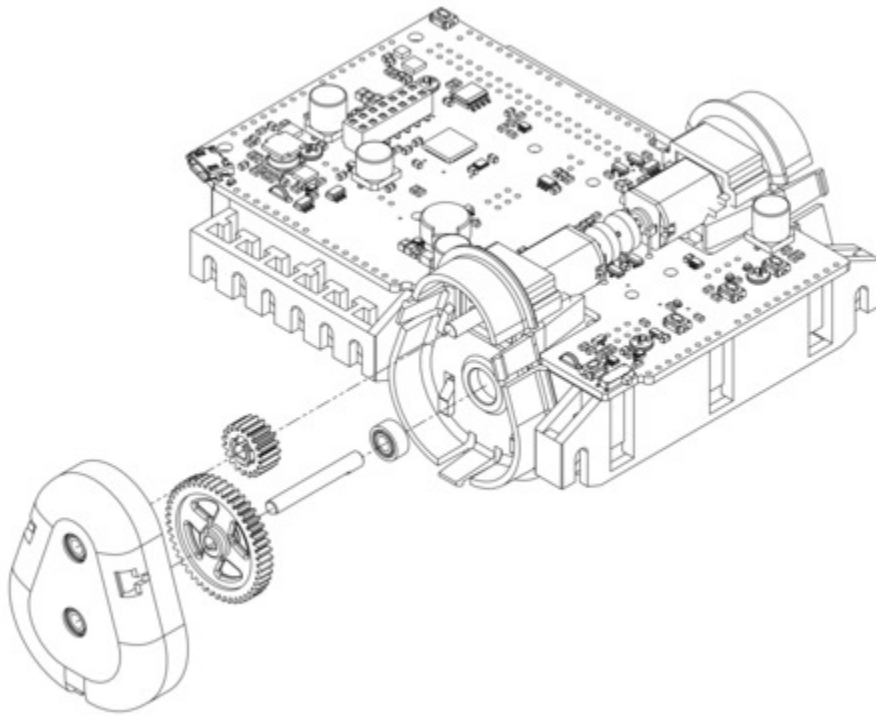
12. Repeat steps 8 through 11 for the second motor (again making sure the + terminal of the motor is toward the longer end of the board).

Gearboxes

13. Choose a gear ratio to use with your Balboa. There are five combinations of the included gears to choose from, each resulting in a different ratio. The **Balboa kit gear ratio chart** [<https://www.pololu.com/file/0J1266/balboa-kit-gear-ratio-chart.pdf>] (447k pdf) details the possible gear ratios and can be used to help identify the gears if printed at 100% scale. Note that the tooth count is also indicated on the side of the output gears.
14. Press two ball bearings into the gearbox cover.



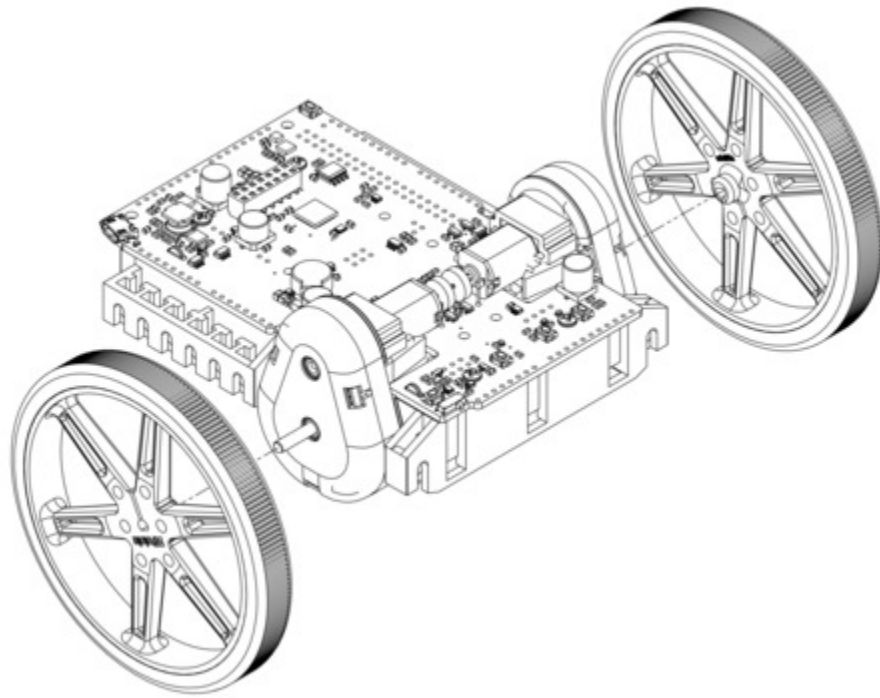
15. Place another ball bearing into the gearbox housing on the chassis and insert the round side of the 3 mm D-shaft (the D-shape should be facing outwards). Next, press your selected gears onto the two shafts, making sure they align properly, and install the gearbox cover. Double check that all three clips have snapped into place.



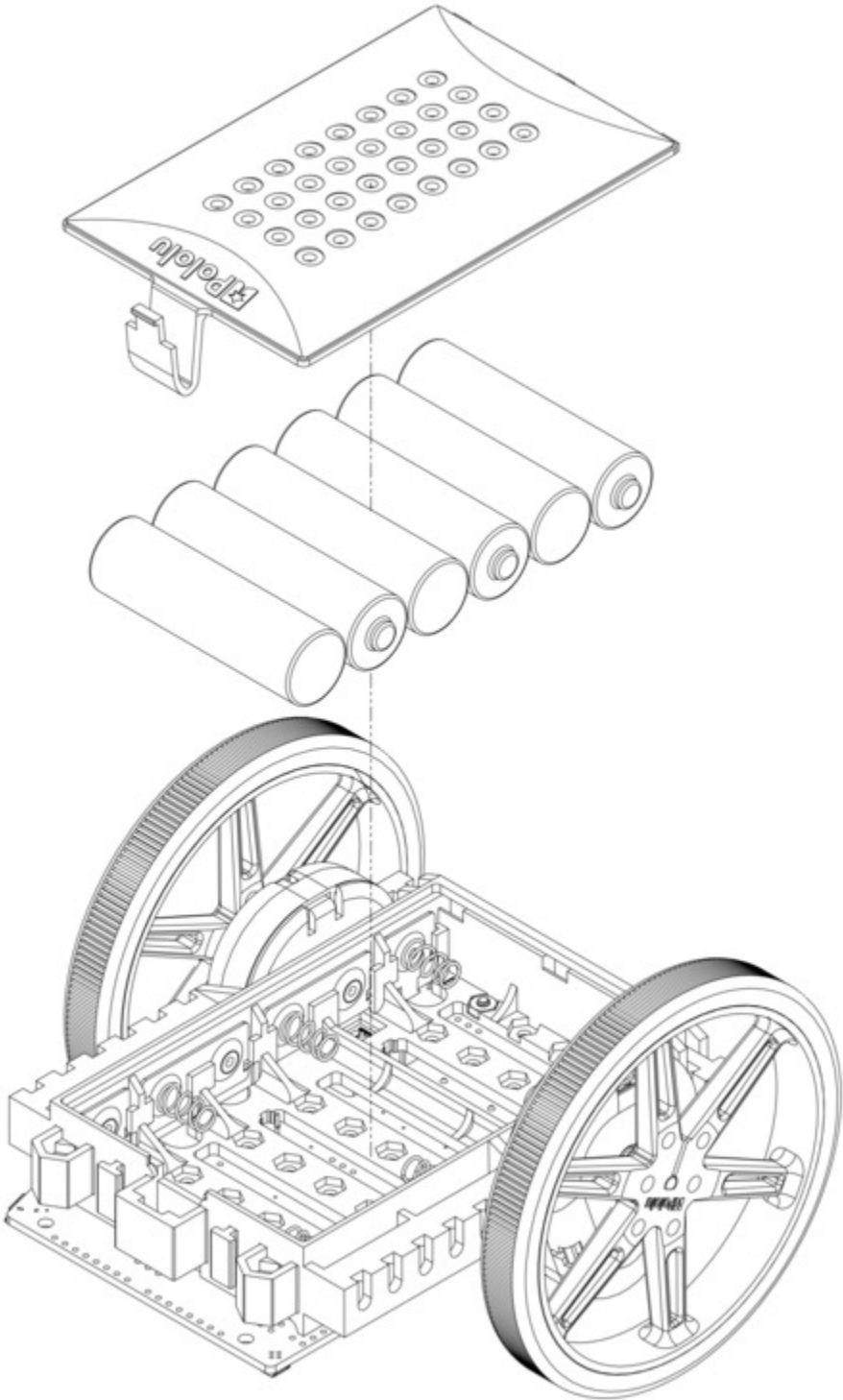
16. Repeat steps 14 and 15 to assemble the other gearbox, making sure to use the same gear ratio.

Wheels and batteries

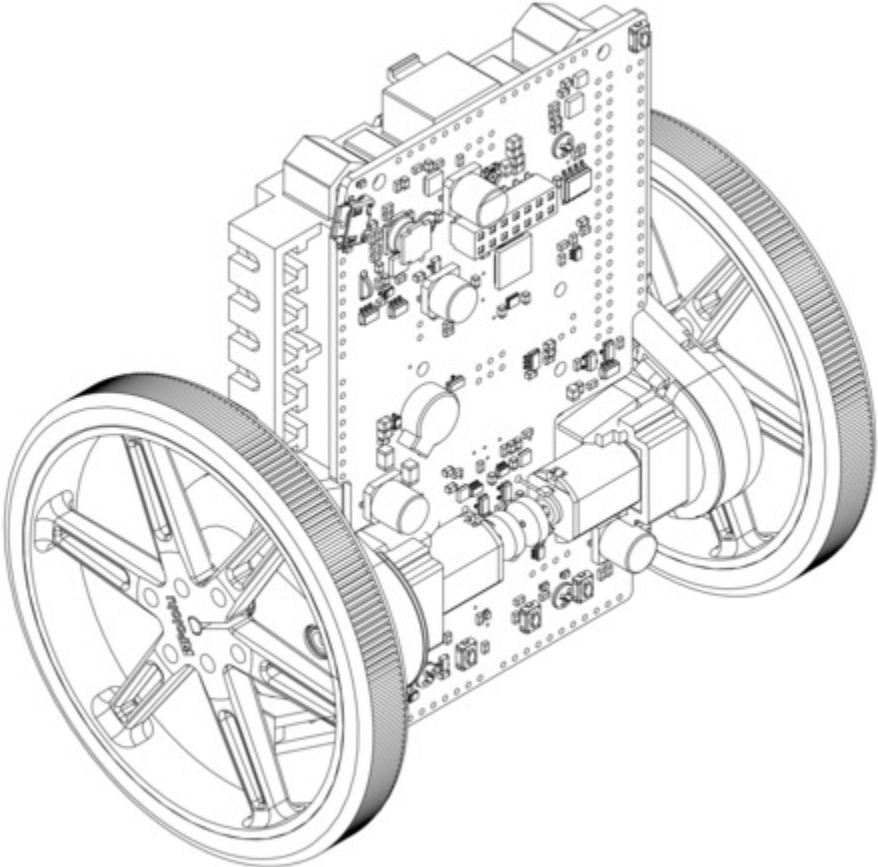
17. Press the wheels onto the output shafts of the gearboxes until the shaft is flush with the outer surface of the wheel. One way to do this is to set the wheel on a flat surface and line the chassis up with it so that the flat part of the motor's D-shaft aligns correctly with the wheel. Then, lower the chassis, pressing the motor shaft into the wheel until it contacts the surface.



18. Install six new or freshly charged AA batteries in the battery compartment (we recommend using rechargeable **AA NiMH cells** [<https://www.pololu.com/product/1003>]). The correct orientation for the batteries is indicated by the battery-shaped holes in the Balboa chassis as well as the + and – indicators in the battery compartment of the chassis. Once they are installed, secure the battery compartment cover.

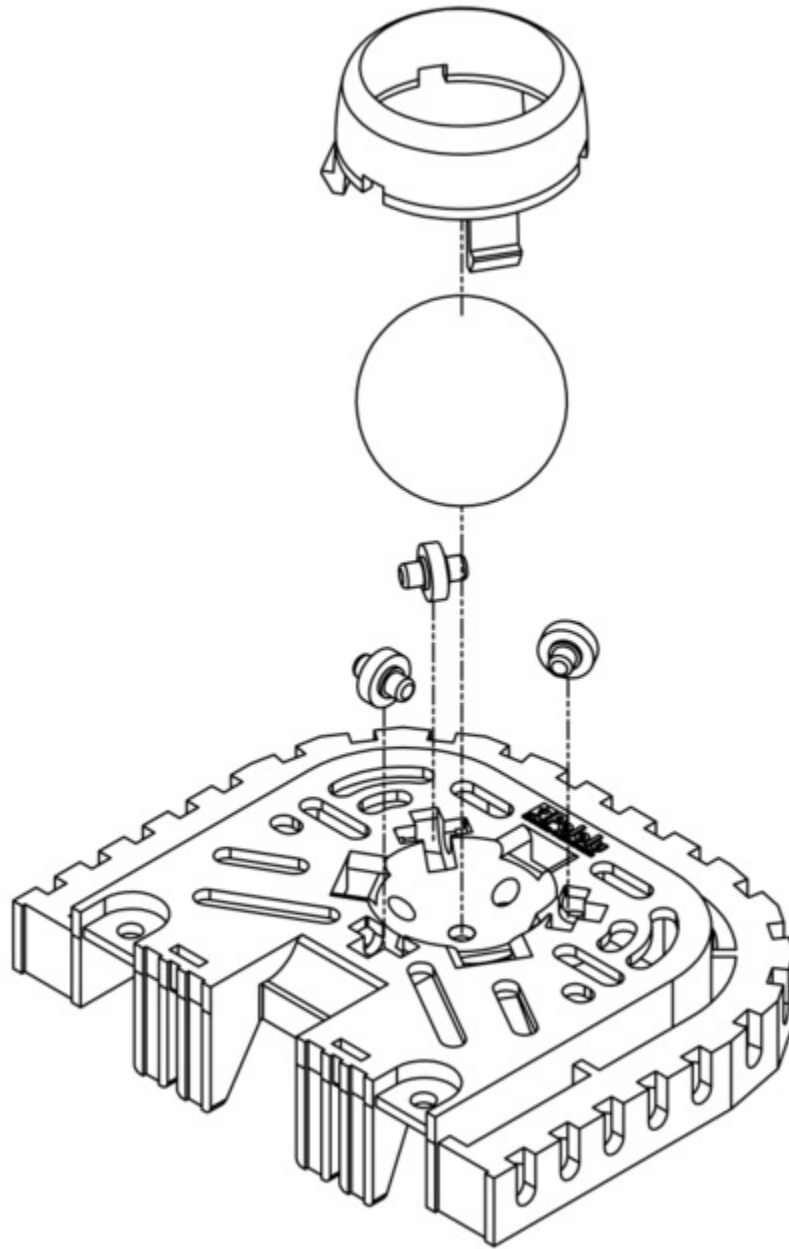


The basic assembly of your Balboa chassis is now complete!

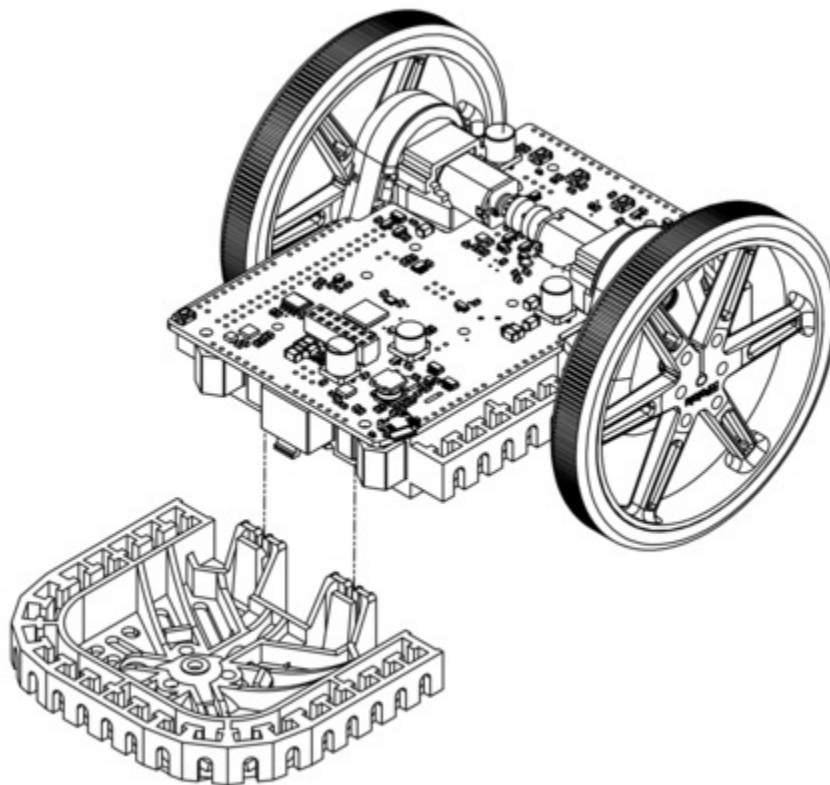


Adding the Stability Conversion Kit

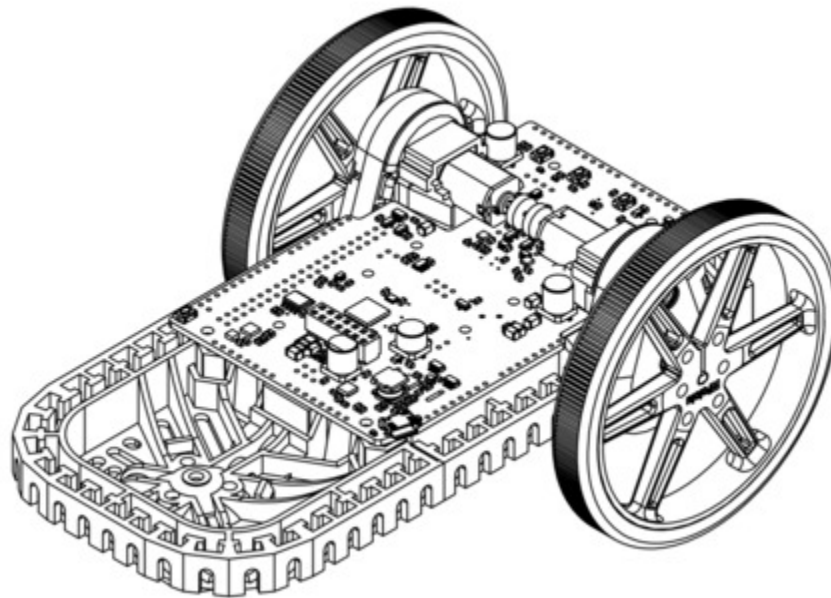
If you have the **Stability Conversion Kit for the Balboa** [<https://www.pololu.com/product/3572>], you can use it to provide a smooth third point of contact for traditional differential-drive applications. Additionally, the extension piece can be used (with or without the ball caster) to make the Balboa taller and give it more mounting options. To assemble the optional ball caster, start by placing the rollers into the cutouts in the Stability Conversion Kit. Next, place the 1" plastic ball on the top of the three rollers and push the ball caster retention clip over the ball and into the chassis so the three legs snap into their respective mounting slots. You should hear a clicking sound when the retention clip is properly engaged.



Align the slots on the Stability Conversion Kit with the rails on the Balboa chassis and slide the two pieces together until the clips snap into place. Optionally, you can use the two mounting holes (located just outside of the clips) to further secure the Stability Conversion Kit to the Balboa chassis. These mounting holes are intended for M3 screws and nuts.

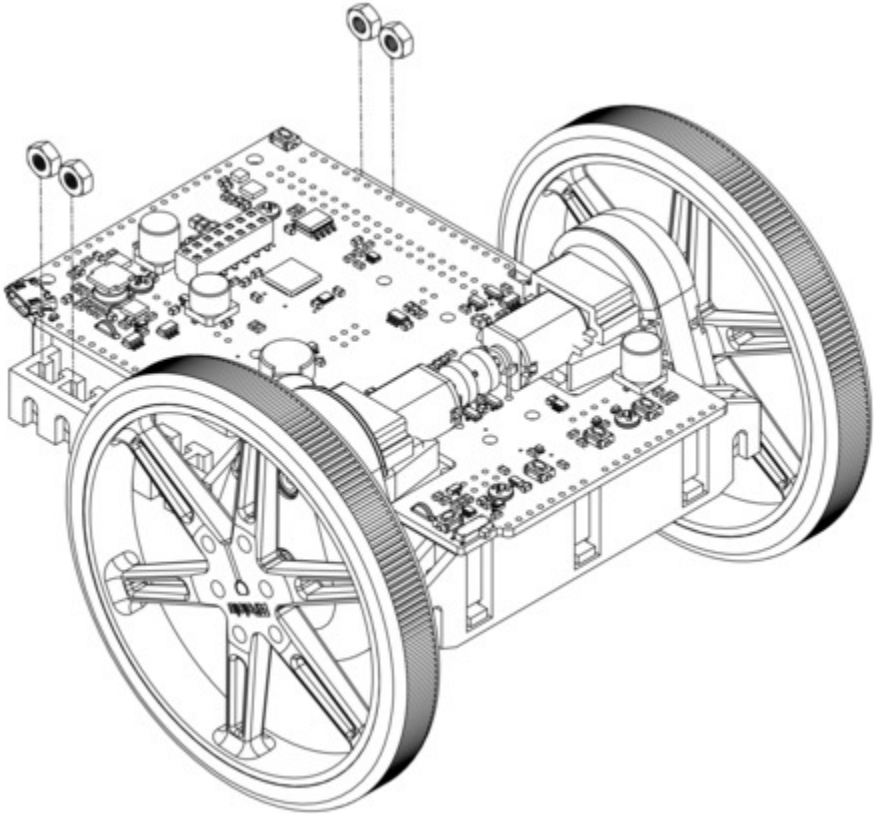


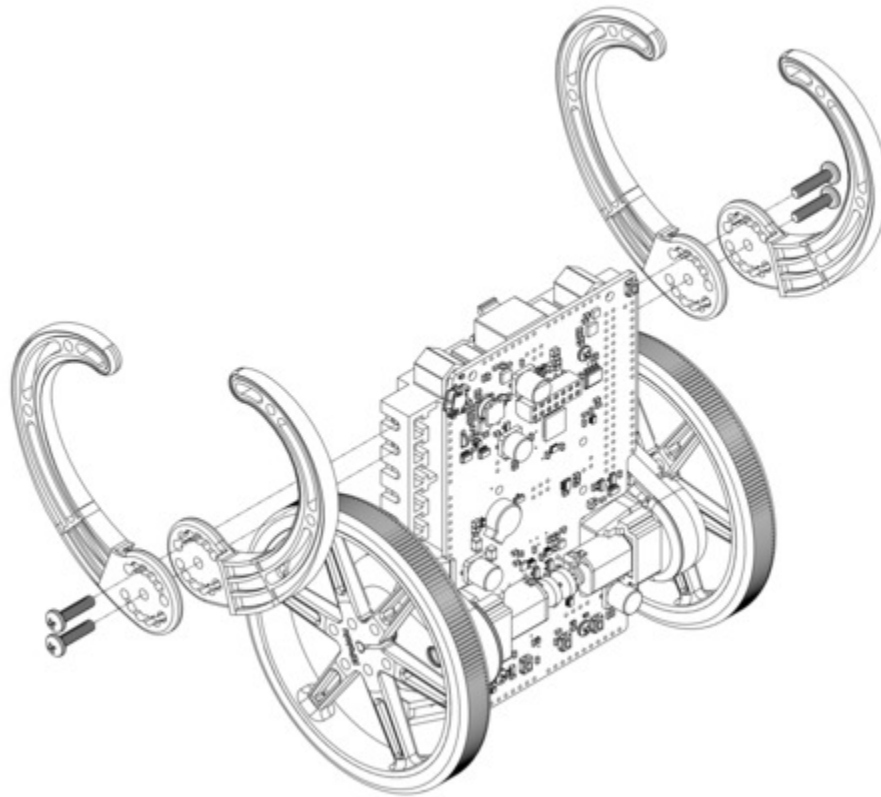
To remove the Stability Conversion Kit from the Balboa, push on the extension piece while simultaneously pulling back on the clips. If you have the Balboa 32U4 control board (or other electronics) mounted on the Balboa chassis, you might consider using a small screwdriver to help reach the clips.



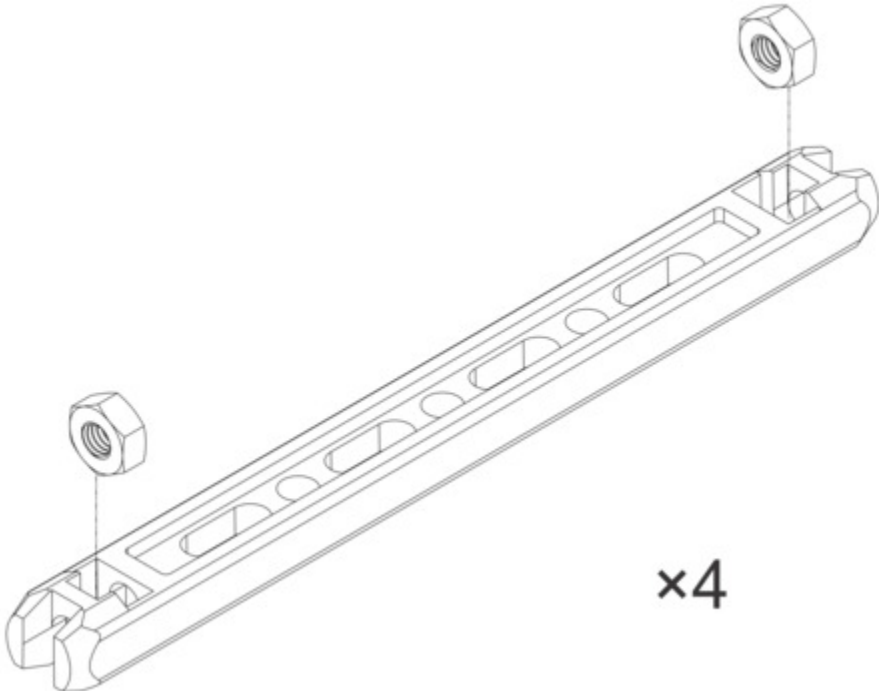
Adding protection against falls

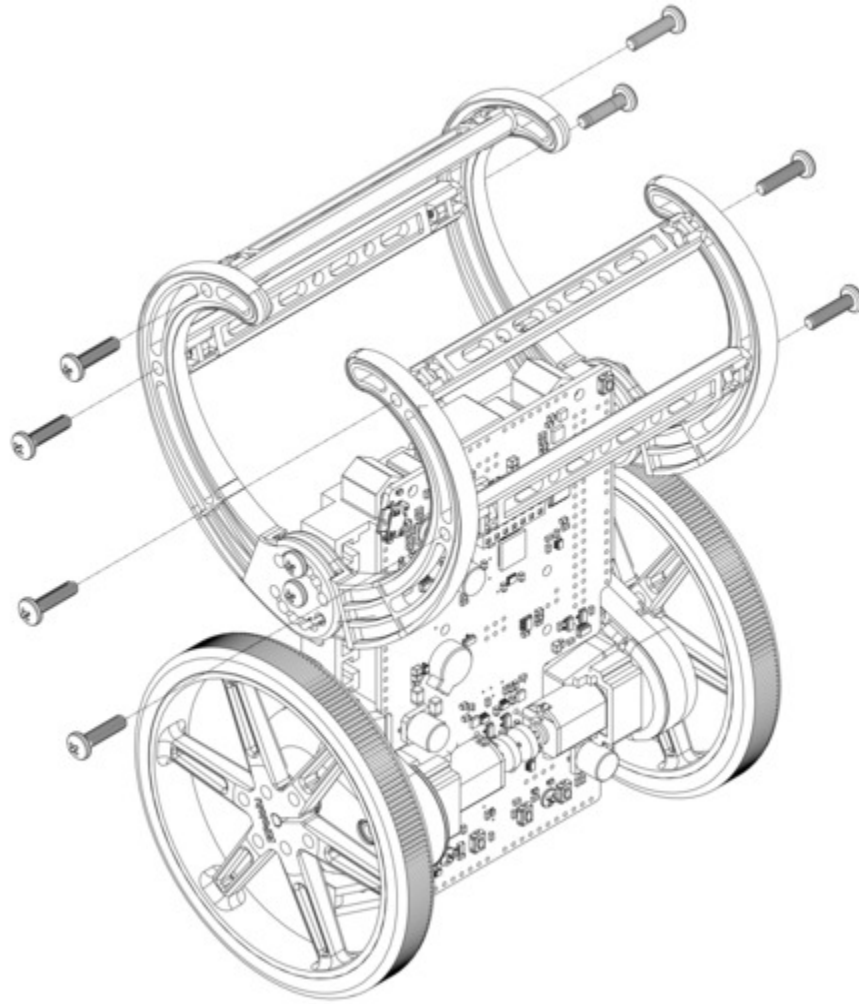
When you are using the Balboa as a balancing robot, it is important to protect the electronics from hard falls that could damage them. In general, we recommend running the Balboa on soft surfaces, such as carpet. It also helps to install the bumper cage kit so the bumper will hit the ground before the electronics. The bumper cage has numerous mounting holes that can be used to adjust the positioning. Details about the various mounting options can be found in **Section 3.12**. The bumper cage mounts to the side rails of the Balboa chassis with M3 screws (12 mm length) and nuts. The bumper cage is made up of four bumper skids and four bumper cage cross bars. The pictures below show the process of mounting the bumper skids.



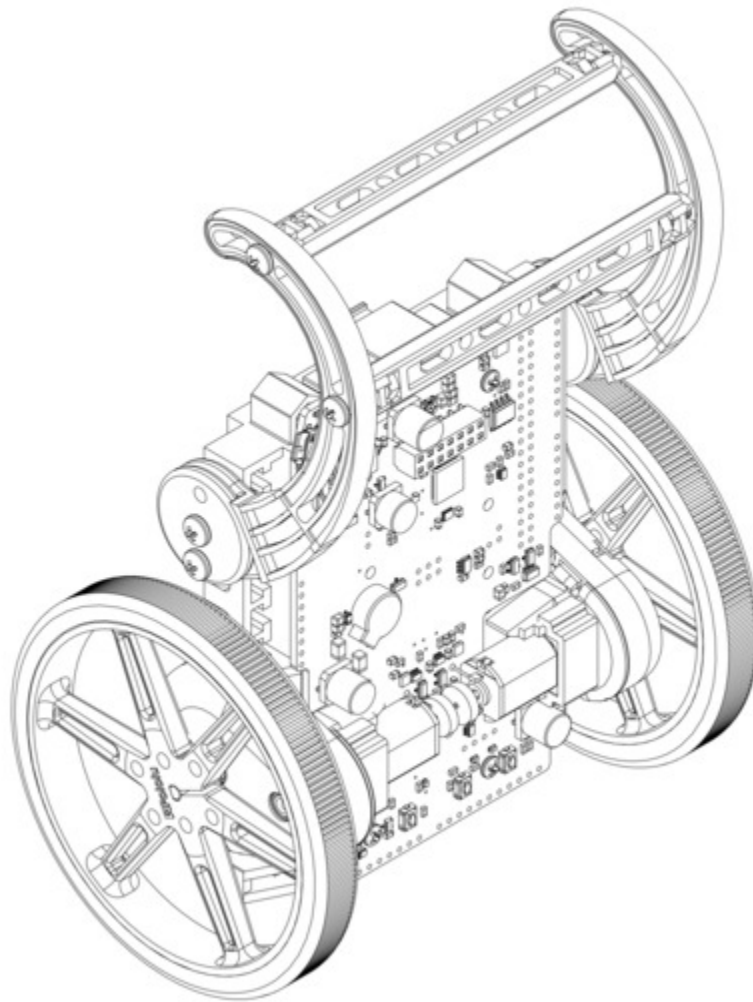


The bumper cage cross bars (shown below) help stabilize the bumper cage and can be installed in various locations, as needed, along the slots or in the designated mounting holes on each bumper skid. They can be rotated before tightening down the mounting screws to better accommodate additional hardware.





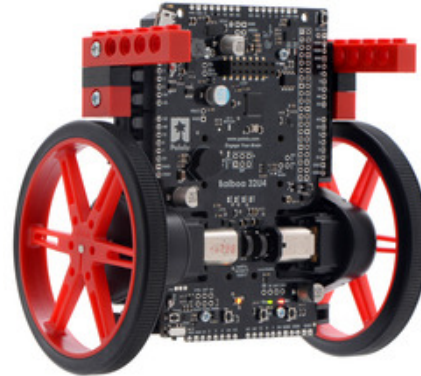
The bumper cage also comes with two spacers, which allow just one side of the bumper cage to be used. This is achieved by substituting one set of bumper skids with the spacers.



Home-made bumper cages could also be used to not only protect electronics, but also add uniqueness and creativity to your robot. The pictures below show two such home-made examples:



Balboa 32U4 Balancing Robot with 80×10mm wheels and 3D-printed arms.



Balboa 32U4 Balancing Robot with 80×10mm wheels and arms made from LEGO blocks.

We have made the arms in the left picture **available on Thingiverse** [<https://www.thingiverse.com/thing:2163695>] so those with access to 3D printers can print their own. For everyone else, you can improvise your own bumpers using everyday objects, like LEGO blocks, wood, or cardboard, and mount them to the side rails of the chassis with M3 screws and **nuts** [<https://www.pololu.com/product/1069>] (the screws in the LEGO-arm picture are 12 mm long).

5. Programming the Balboa 32U4

The Balboa 32U4 control board is designed to be programmed over USB from the **Arduino IDE** [<https://www.arduino.cc/en/software/>]. It can be programmed from Windows, Linux, and Mac OS X. The ATmega32U4 on the control board comes preloaded with the same USB bootloader as the **A-Star 32U4 family** [<https://www.pololu.com/category/149/a-star-programmable-controllers>] of general-purpose programmable ATmega32U4 boards. The following sections will help you get started programming your Balboa 32U4.

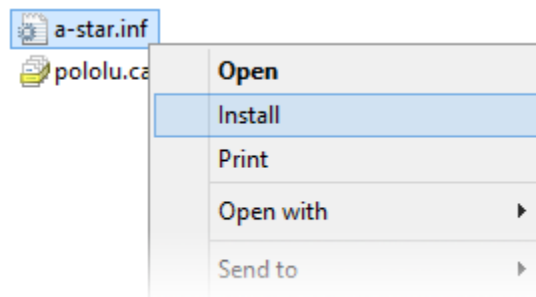
5.1. Installing Windows drivers



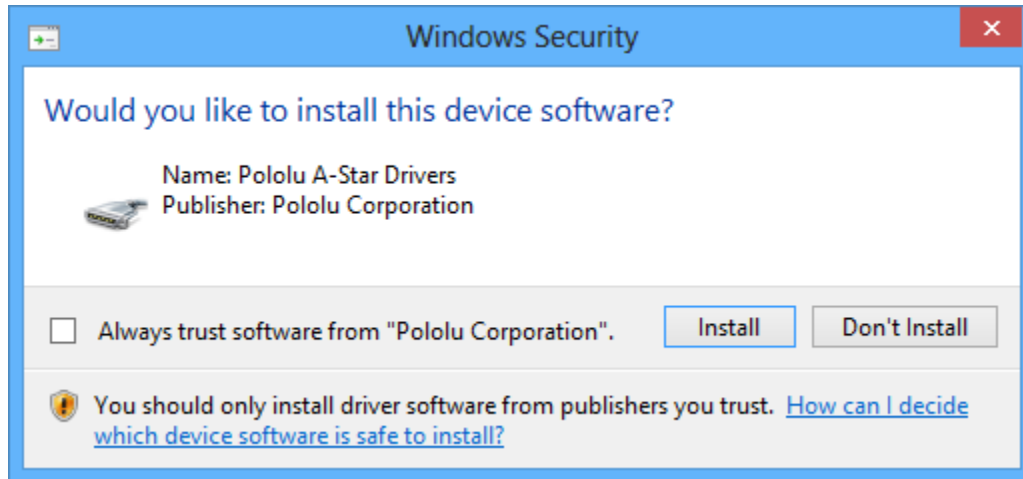
If you use Windows XP, you will need to have either Service Pack 3 or Hotfix KB918365 installed before installing the A-Star drivers. Some users who installed the hotfix have reported problems that were solved by upgrading to Service Pack 3, so we recommend Service Pack 3 over the hotfix.

Before you connect your Pololu A-Star 32U4 (or another of our 32U4 family of boards) to a computer running Microsoft Windows, you should install its drivers:

1. Download the **A-Star Windows Drivers** [<https://www.pololu.com/file/0J1240/a-star-windows-1.3.0.0.zip>] (7k zip) and extract the ZIP file to a temporary folder on your computer. (These files are also available in the “drivers” directory from the **A-Star repository on GitHub** [<https://github.com/pololu/a-star>].)
2. Open the “a-star-windows” folder. Right-click on “a-star.inf” and select “Install”.



3. Windows will ask you whether you want to install the drivers. Click “Install” (Windows 10, 8, 7, and Vista) or “Continue Anyway” (Windows XP).



4. Windows will not tell you when the installation is complete, but it should be done after a few seconds.

Windows 10, Windows 8, Windows 7, and Windows Vista users: After installing the drivers, your computer should automatically recognize the device when you connect it via USB. No further action from you is required. However, the first time you connect an A-Star device to your computer, Windows will take several seconds to recognize the device and configure itself properly. The first time you program the device, Windows will again take several seconds to recognize the A-Star USB bootloader, and this could cause the programming operation to fail the first time. Also, Windows will need to re-recognize the device and the bootloader if you connect the board to another USB port that it has not been connected to before.

Windows XP users: After installing the drivers, you will need to follow steps 5–9 for each new A-Star device you connect to your computer. You will also need to follow these steps the first time you attempt to program the device in order to make Windows recognize the bootloader, and when you connect the device to a different USB port that it has not been connected to before.

5. Connect the device to your computer's USB port.
6. When the "Found New Hardware Wizard" is displayed, select "No, not this time" and click "Next".
7. On the second screen of the "Found New Hardware Wizard", select "Install the software automatically" and click "Next".
8. Windows XP will warn you again that the driver has not been tested by Microsoft and recommend that you stop the installation. Click "Continue Anyway".
9. When you have finished the "Found New Hardware Wizard", click "Finish".

COM port details

After installing the drivers and plugging in an A-Star, in the “Ports (COM & LPT)” category of the Device Manager, you should see a COM port for the A-Star’s running sketch named “Pololu A-Star 32U4”.

You might see that the COM port is named “USB Serial Device” in the Device Manager instead of having a descriptive name. This can happen if you are using Windows 10 or later and you plugged the A-Star into your computer before installing our drivers for it. In that case, Windows will set up your A-Star using the default Windows serial driver (usbser.inf), and it will display “USB Serial Device” as the name for the port. The port will still be usable, but it will be hard to tell if it is the right one because of the generic name shown in the Device Manager. We recommend fixing the names in the Device Manager by right-clicking on each “USB Serial Device” entry, selecting “Update Driver Software...”, and then selecting “Search automatically for updated driver software”. Windows should find the drivers you already installed, which contain the correct name for the port.

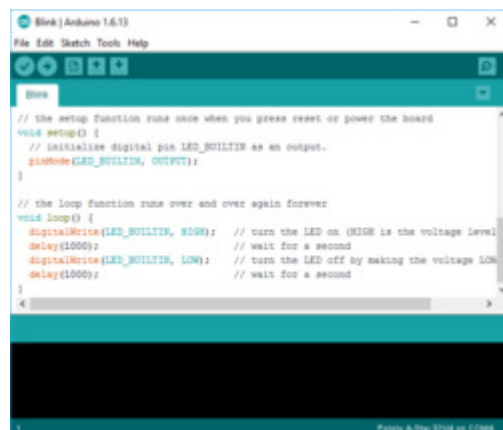
If you are using Windows 10 or later and choose not to install the drivers, the A-Star will still be usable. To tell which “USB Serial Device” in your Device Manager is the A-Star, double-click on each one and look at the “Hardware Ids” property in the “Details” tab. An A-Star running a sketch will have the ID `USB\VID_1FFB&PID_2300&MI_00`, while an A-Star in bootloader mode will have the ID `USB\VID_1FFB&PID_0101`.

If you want to change the COM port numbers assigned to your A-Star, you can do so using the Device Manager. Double-click a COM port to open its properties dialog, and click the “Advanced...” button in the “Port Settings” tab.

5.2. Programming using the Arduino IDE

Our 32U4 family of boards can be programmed from the popular Arduino integrated development environment (IDE). The Arduino IDE is a cross-platform, open source application that integrates a C++ code editor, the GNU C++ compiler, and a program upload utility. To get started programming your device with the Arduino IDE (version 1.6.4 or later), follow these steps:

1. Download the Arduino IDE from the **Arduino Download page** [<https://www.arduino.cc/en/software/>], install it, and start it.
2. In the Arduino IDE, open the **File** menu (Windows/Linux) or the **Arduino** menu (macOS) and select “Preferences”.

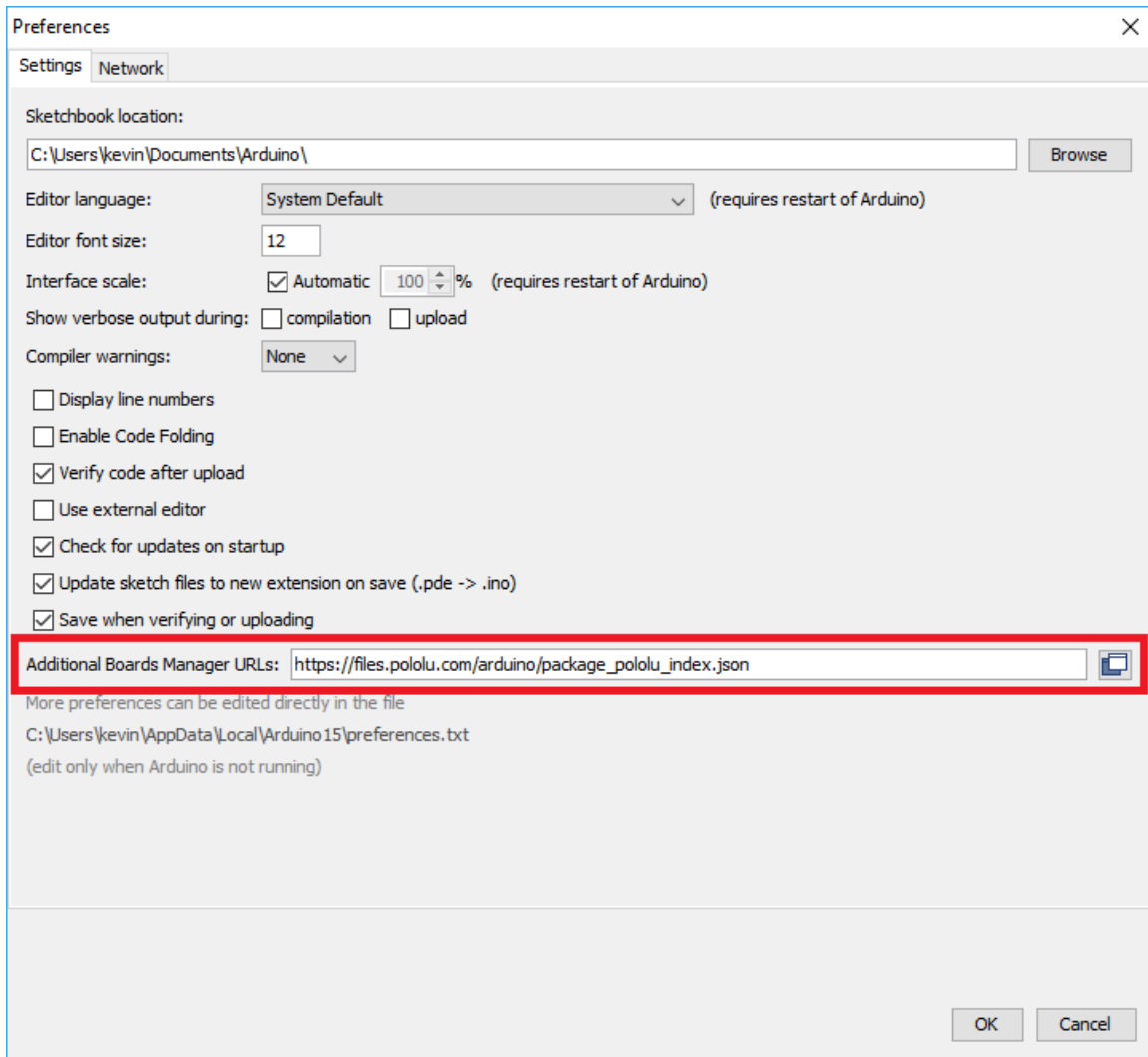


Programming the A-Star 32U4 from the Arduino IDE.

3. In the Preferences dialog, find the “Additional Boards Manager URLs” text box (highlighted in the picture below). Copy and paste the following URL into this box:

https://files.pololu.com/arduino/package_pololu_index.json

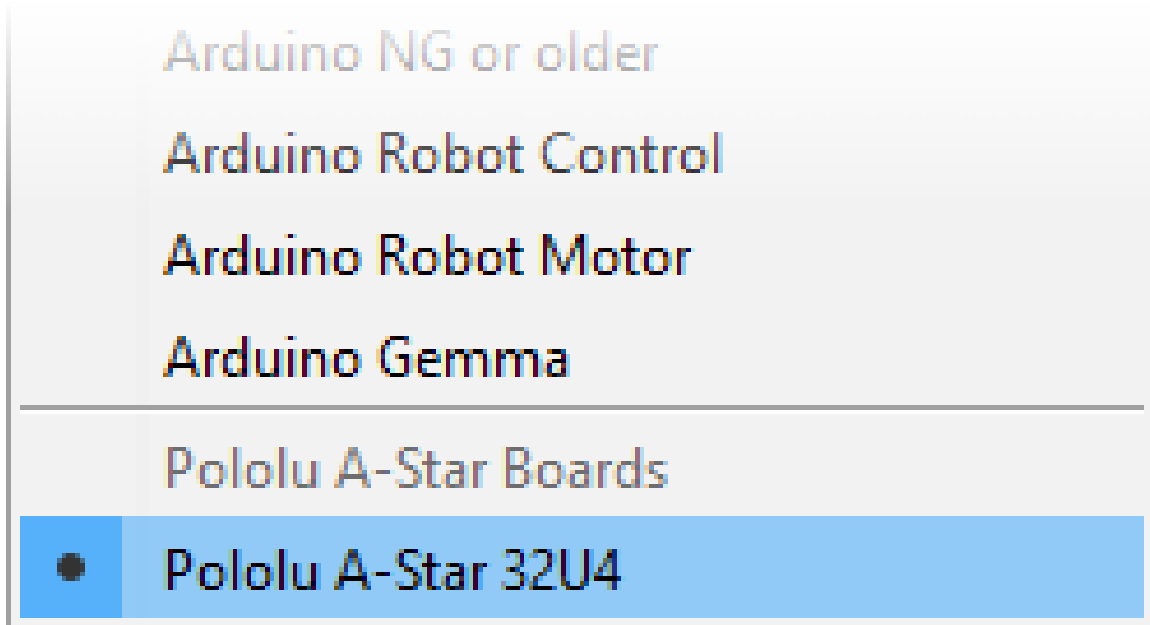
If there are already other URLs in the box, you can either add this one separated by a comma **or** click the button next to the box to open an input dialog where you can add the URL on a new line.



Adding a Boards Manager index for Pololu boards in the Arduino IDE's Preferences dialog.

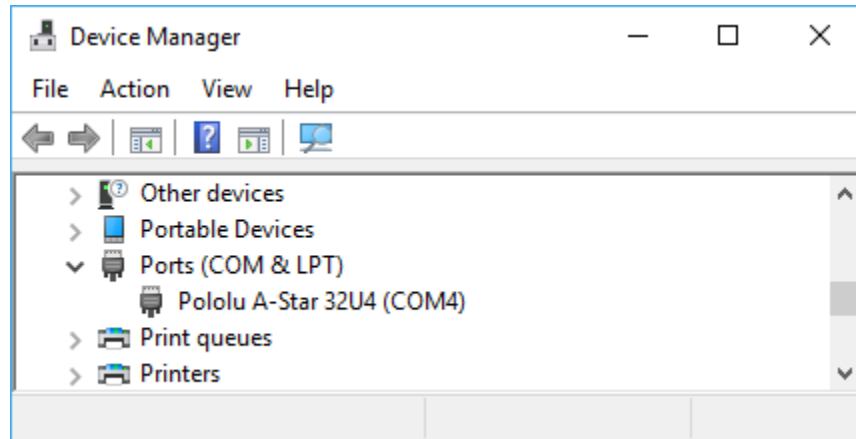
4. Click the “OK” button to close the Preferences dialog.

5. In the **Tools > Board** menu, select “Boards Manager...” (at the top of the menu).
6. In the Boards Manager dialog, search for “Pololu A-Star Boards”.
7. Select the “Pololu A-Star Boards” entry in the list, and click the “Install” button.
8. After the installation finishes, click the “Close” button to close the Boards Manager dialog.
9. In the **Tools > Board** menu, select the “Pololu A-Star 32U4” entry. If you do not see your device listed in the Board menu, try restarting the Arduino IDE.



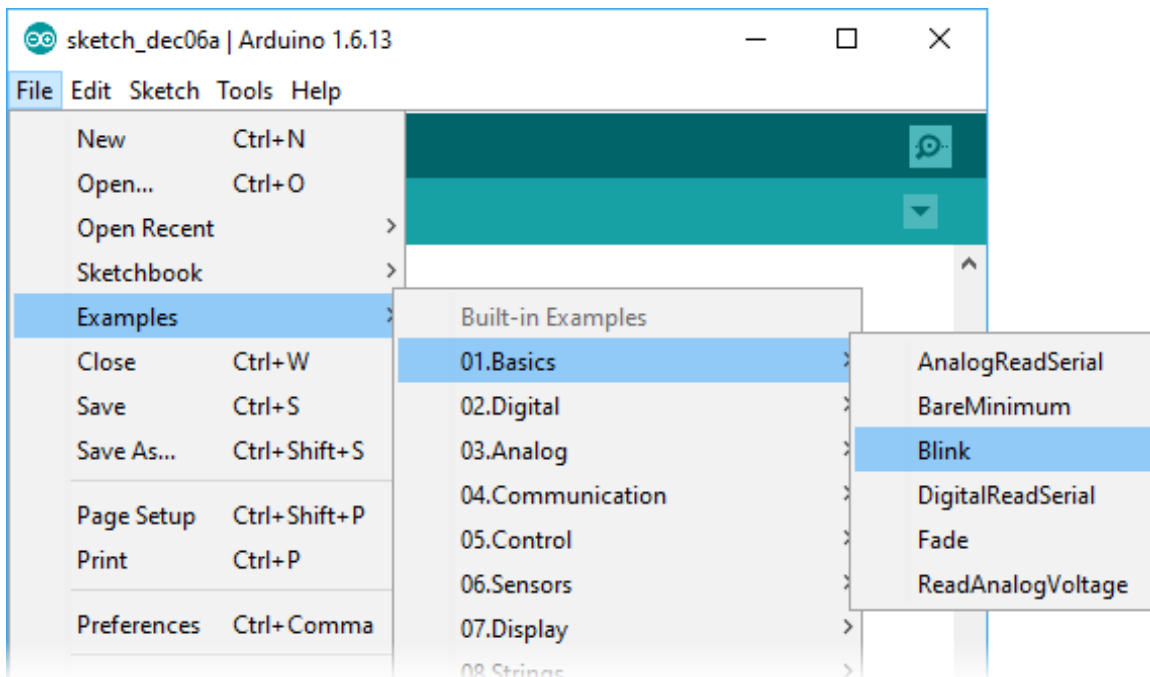
Selecting the Pololu A-Star 32U4 in the Boards menu.

10. In the **Tools > Port** menu, select the port for the device. On Windows you can determine what COM port the device is assigned to by looking at the “Ports (COM & LPT)” section of the Device Manager. On Linux, the port name will begin with “/dev/ttyACM”. On Mac OS X, the port name will begin with “/dev/tty.usbmodem”.



Windows 10 Device Manager showing the A-Star's virtual COM port.

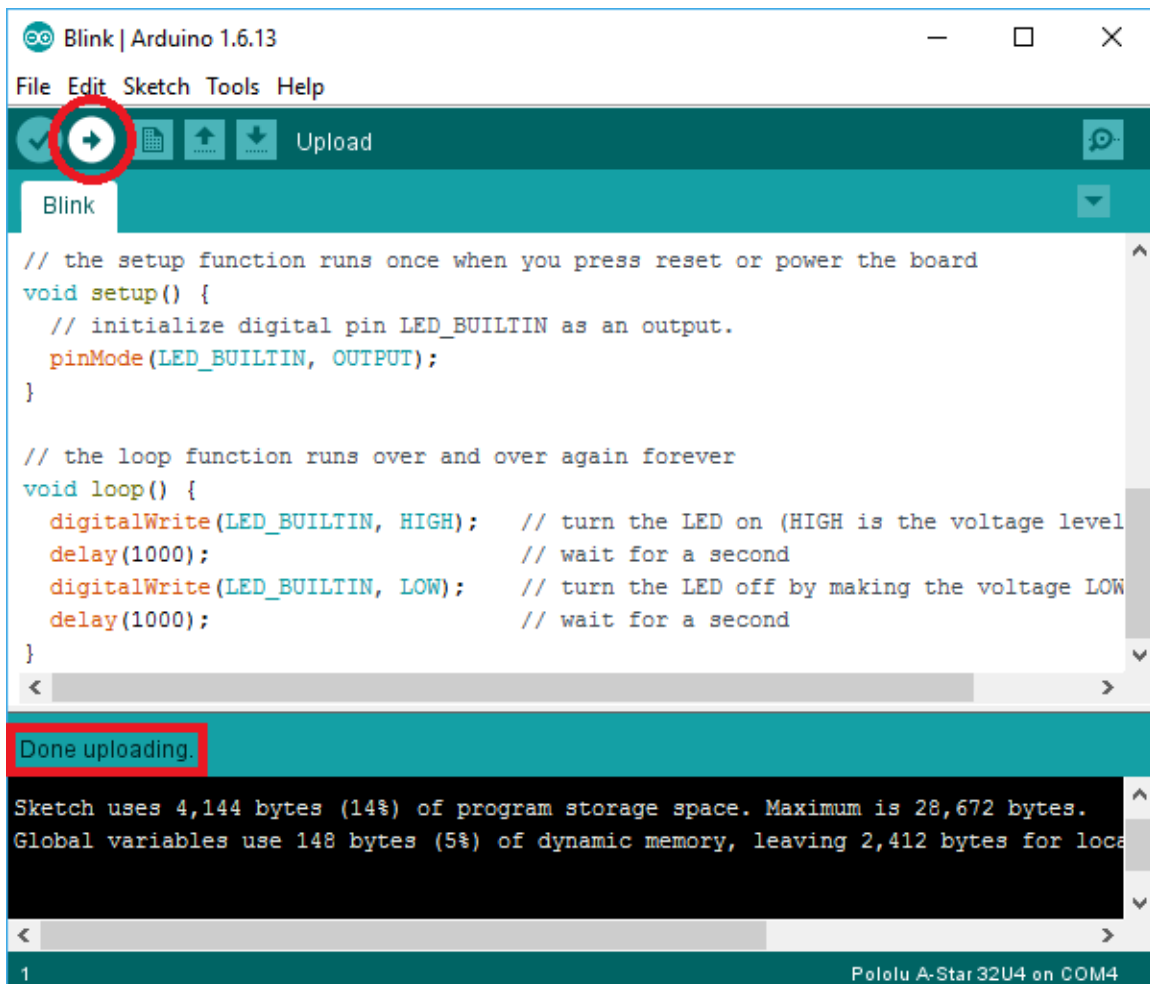
11. Open up the "Blink" Arduino example, which can be found under **File > Examples > 01.Basics > Blink**. The code in this example will blink the yellow LED. When you select the Blink example, a new Arduino IDE window will open up. It is OK to close the first window.



Selecting the Blink example in the Arduino IDE.

12. Press the "Upload" button to compile the sketch and upload it to the device. If everything goes correctly, you will see the message "Done uploading" appear near the bottom of the window. If you are using Windows and you have not previously programmed an A-Star device on this

USB port, then Windows might take several seconds to recognize the A-Star bootloader. The bootloader times out after 8 seconds and goes back to running the sketch, so the upload might fail if Windows does not recognize it quickly enough. If this happens, try again. If you are using Windows XP and have not programmed an A-Star on this USB port, you will have to go through the Found New Hardware Wizard again as described in the previous section, but the second time you try to upload it should work. If the Arduino IDE has trouble connecting to the port or using it, try unplugging the device, closing any programs that might be using the serial port, restarting the Arduino IDE, and then plugging the device back in.



Uploading a sketch to the A-Star using the Arduino IDE.

13. If you uploaded the Blink sketch, then the yellow LED should be blinking once every two seconds. However, we ship some A-Stars with that same example already programmed onto it, so you might not be convinced that anything has changed. Try changing the delay values in the sketch to something else and uploading again to see if you can change the speed of

the LED.



The A-Star 32U4 boards are similar enough to the Arduino Leonardo that you do not actually have to install the add-on. If you want to, you can just select the “Arduino Leonardo” board in the Arduino IDE. Note that if you upload a sketch to the device this way, your computer will then recognize it as a Leonardo (for example, its entry in the Windows Device Manager will display “Arduino Leonardo”).

After you succeed in programming your device from the Arduino IDE, there are many resources you can use to learn more:

- The Arduino IDE has many **examples** [<http://arduino.cc/en/Tutorial/HomePage>] that can run on A-Stars.
- The Arduino website has a **Language Reference** [<http://arduino.cc/en/Reference/HomePage>], a wiki called the **The Arduino Playground** [<http://playground.arduino.cc/>], and other resources.
- The A-Star 32U4 boards are similar to the **Arduino Leonardo** [<https://www.pololu.com/product/2192>] and **Arduino Micro** [<https://www.pololu.com/product/2188>], so you can search the Internet for relevant projects that use one of those boards.
- The Related Resources section lists many more resources.

Disabling ModemManager in Linux

If you are using Linux and have trouble following the instructions above, your issue might be caused by a program called ModemManager. This program automatically connects to serial ports and sends modem commands to them, interfering with other software using those ports. You can run `ps ax | grep -i Modem` to see if ModemManager is running. On Ubuntu, the command to permanently disable ModemManager is:

```
sudo systemctl disable ModemManager
```

5.3. Programming using avr-gcc and AVRDUDE

This section explains how to program our 32U4 family of boards using the avr-gcc toolchain and AVRDUDE. This section is intended for advanced users who do not want to use the Arduino IDE as described in the previous section.

Getting the prerequisites

If you are using Windows, we recommend downloading **WinAVR** [<http://winavr.sourceforge.net/>], which contains the avr-gcc toolchain and a command-line utility called **AVRDUDE** [<http://www.nongnu.org/>]

avrdude] that can be used to upload programs to the A-Star bootloader. If the version of GNU Make that comes with WinAVR crashes on your computer, we recommend using the **Pololu version of GNU Make** [<https://github.com/pololu/make/releases>].

If you are using macOS, we recommend first installing **Homebrew** [<https://brew.sh/>]. Then run the following commands to install AVRDUDE and **homebrew-avr** [<https://github.com/osx-cross/homebrew-avr/>]:

```
brew install avrdude
xcode-select --install
brew tap osx-cross/avr
brew install avr-gcc
```

If you are using Linux, you will need to install `avr-gcc`, `avr-libc`, and `AVRDUDE`. Ubuntu users can get the required software by running:

```
sudo apt-get install gcc-avr avr-libc avrdude
```

After you have installed the prerequisites, open a command prompt and try running these commands to make sure all the required utilities are available:

```
avr-gcc -v
avr-objcopy -v
make -v
avrdude
```

If any of those commands fail, make sure the desired executable is installed on your computer and make sure that it is in a directory listed in your `PATH` environment variable.

Compiling an example program

Copy the following code to a file named “main.c”:

```
1  #define F_CPU 16000000
2  #include <avr/io.h>
3  #include <util/delay.h>
4
5  int main()
6  {
7      DDRC |= (1 << DDC7);    // Make pin 13 be an output.
8      while(1)
9      {
10         PORTC |= (1 << PORTC7); // Turn the LED on.
11         _delay_ms(500);
12         PORTC &= ~(1 << PORTC7); // Turn the LED off.
13         _delay_ms(500);
14     }
15 }
```

In the same folder, create a file named “Makefile” with the following contents:

```
PORT=\\\\.\\GLOBALROOT\\Device\\USBSER000
```

```
MCU=atmega32u4
CFLAGS=-g -Wall -mcall-prologues -mmcu=$(MCU) -Os
LDFLAGS=-Wl,-gc-sections -Wl,-relax
CC=avr-gcc
TARGET=main
OBJECT_FILES=main.o

all: $(TARGET).hex

clean:
    rm -f *.o *.hex *.obj *.hex

%.hex: %.obj
    avr-objcopy -R .eeprom -O ihex $< $@

%.obj: $(OBJECT_FILES)
    $(CC) $(CFLAGS) $(OBJECT_FILES) $(LDFLAGS) -o $@

program: $(TARGET).hex
    avrdude -p $(MCU) -c avr109 -P $(PORT) -U flash:w:$(TARGET).hex
```

Make sure that the `PORT` variable in the Makefile is the name of the device's virtual serial port. In Windows, `\\\\.\\GLOBALROOT\\Device\\USBSER000` should work if the A-Star is the only USB device connected that is using the `usbser.sys` driver, but you can change it to be the actual name of the COM port (e.g. `COM13`).

In a command prompt, navigate to the directory with the Makefile and `main.c`. If you run the command `make`, the code should get compiled and produce a file named "main.hex".

Programming

To program the A-Star device, you will need to get it into bootloader mode first. One way to do this is to reset the AVR twice within 750 ms. Most of the boards in our 32U4 family have a reset button that can be used to reset the board. On any of our 32U4 family of boards, a pushbutton can be connected between the GND and RST pins to serve as a reset button, or you can use a wire. Once the device is in bootloader mode, quickly run the command `make program` to program it. If you wait longer than 8 seconds, the A-Star bootloader will exit and the AVR will go back to running the user program.

6. Balboa 32U4 Arduino library

The Balboa 32U4 can be programmed from the Arduino IDE as described in the preceding sections.

To help interface with all the on-board hardware on the control board, we provide the **Balboa32U4 library**. The **Balboa32U4 library documentation** [<https://pololu.github.io/balboa-32u4-arduino-library/>] provides detailed information about the library, and the library comes with several example sketches.

If you are using version 1.6.2 or later of the Arduino software (IDE), you can use the Library Manager to install this library:

1. In the Arduino IDE, open the “Sketch” menu, select “Include Library”, then “Manage Libraries...”.
2. Search for “Balboa32U4”.
3. Click the Balboa32U4 entry in the list.
4. Click “Install”.

If this does not work, you can manually install the library:

1. Download the **latest release archive from GitHub** [<https://github.com/pololu/balboa-32u4-arduino-library>] and decompress it.
2. Rename the folder “balboa-32u4-arduino-library-master” to “Balboa32U4”.
3. Move the “Balboa32U4” folder into the “libraries” directory inside your Arduino sketchbook directory. You can view your sketchbook location by opening the “File” menu and selecting “Preferences” in the Arduino IDE. If there is not already a “libraries” folder in that location, you should make the folder yourself.
4. After installing the library, restart the Arduino IDE.

After you install the Balboa32U4 library, you can learn more about it by trying the included example sketches and by reading the **Balboa32U4 library documentation** [<https://pololu.github.io/balboa-32u4-arduino-library/>].

To use the inertial sensors on the Balboa 32U4, you might also want to install our **LSM6** [<https://github.com/pololu/lsm6-arduino>] and **LIS3MDL** [<https://github.com/pololu/lis3mdl-arduino>] libraries (the LSM6 library is required to run the Balboa32U4 library’s “Balancer” example).

If you are using your Balboa 32U4 with a Raspberry Pi, you might also want to make use of our **Raspberry Pi slave library for Arduino** [<https://github.com/pololu/pololu-rpi-slave-arduino-library>], which sets up the A-Star as an I²C slave and helps establish communication with a Raspberry Pi master. See **Section 3.8** for more information about the Raspberry Pi interface.

7. How to make a Balboa balance

Balancing a two-wheeled robot like the Balboa is a classic problem in control theory, known as the “inverted pendulum”, and there are many approaches to solving it. This section discusses the simple balancing technique in the Balboa **Balancer example** [<https://github.com/pololu/balboa-32u4-arduino-library/tree/master/examples/Balancer>], which uses feedback from the Balboa’s gyroscope and encoders to keep the robot upright.

7.1. Sensor measurements

The key to balancing is the built-in ST **LSM6DS33** [<https://www.pololu.com/product/2736>] IMU chip, which combines a 3D gyroscope and a 3D accelerometer. The Balboa also includes an ST **LIS3MDL** [<https://www.pololu.com/product/2737>] 3-axis magnetometer. These nine sensor channels can be used in software to make an *AHRS* (attitude and heading reference system), a system that gives the robot a sense of its orientation in three dimensions. AHRS software is particularly important in aviation/drone applications, but for basic balancing, you don’t need anything that complicated. In fact, a single gyro channel – the y-axis – is enough to determine the robot’s angle of rotation relative to vertical.

The gyroscope’s y-axis channel measures the Balboa’s forward/backward rate of rotation, in units such as degrees per second. To keep track of its total rotation angle, you need to integrate the gyro reading: periodically check the sensor and multiply the rate of rotation by the time period. Here is the main gyro-related code from our Balboa **Balancer example** [<https://github.com/pololu/balboa-32u4-arduino-library/tree/master/examples/Balancer>], which does exactly that:

```
1 void setup()
2 {
3   // Initialize IMU.
4   Wire.begin();
5   if (!imu.init())
6   {
7     while(true)
8     {
9       Serial.println("Failed to detect and initialize IMU!");
10      delay(200);
11    }
12  }
13  imu.enableDefault();
14  imu.writeReg(LSM6::CTRL2_G, 0b01011000); // 208 Hz, 1000 deg/s
15
16  // Wait for IMU readings to stabilize.
17  delay(1000);
18
19  // Calibrate the gyro.
20  int32_t total = 0;
21  for (int i = 0; i < CALIBRATION_ITERATIONS; i++)
22  {
23    imu.read();
24    total += imu.g.y;
25    delay(1);
26  }
27
28  gYZero = total / CALIBRATION_ITERATIONS;
29 }
30
31 // Call this every 10ms (UPDATE_TIME_MS)
32 void integrateGyro()
33 {
34   // Convert from full-scale 1000 deg/s to deg/s.
35   angleRate = (imu.g.y - gYZero) / 29;
36
37   angle += angleRate * UPDATE_TIME_MS;
38 }
```

The calibration variable `gYZero`, which is calculated during `setup()`, is an important feature. Gyroscopes tend to have a small offset in their readings, which we measure in the example code by taking readings while the robot is at rest. Correcting for the offset makes the angle calculation far more accurate. Once calibrated, the angle should drift at most a few degrees in a minute, which is more than good enough for balancing.

However, integrating the gyro reading actually only determines the total *change* in angle. You still need to pick a good starting value. An easy way to do this is to start the robot in a known position; for example you could initialize `angle` with a value of zero and start the robot from a vertical position. Our balancer example expects the robot to start lying down on its front side, with the angle initialized to 110 degrees.

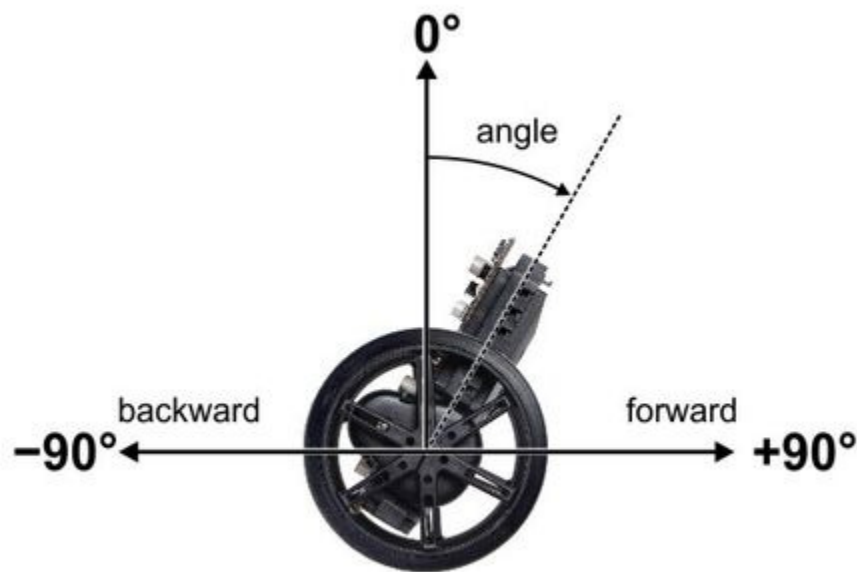
Even after you have calibrated the gyro and estimated the starting angle, your angle measurement will tend to drift over time, maybe a few degrees in a minute. In a full AHRS, you use the accelerometer to eliminate drift, but for a balancing robot we can use a simpler trick: if the robot is successfully

balancing, we know that on average, it must be close to vertical. So if we constantly, gradually shift the `angle` variable towards zero, it will not build up any significant error due to gyro drift. In our balancer example, that just takes a single line of code, called whenever the robot is balancing:

```
1 | angle = angle * 999 / 1000;
```

Now that we have good measurements of the robot's angle and rate of rotation, we can talk about how to make it actually balance. The next section discusses the approach to balancing used in our example code.

7.2. An example balancing algorithm

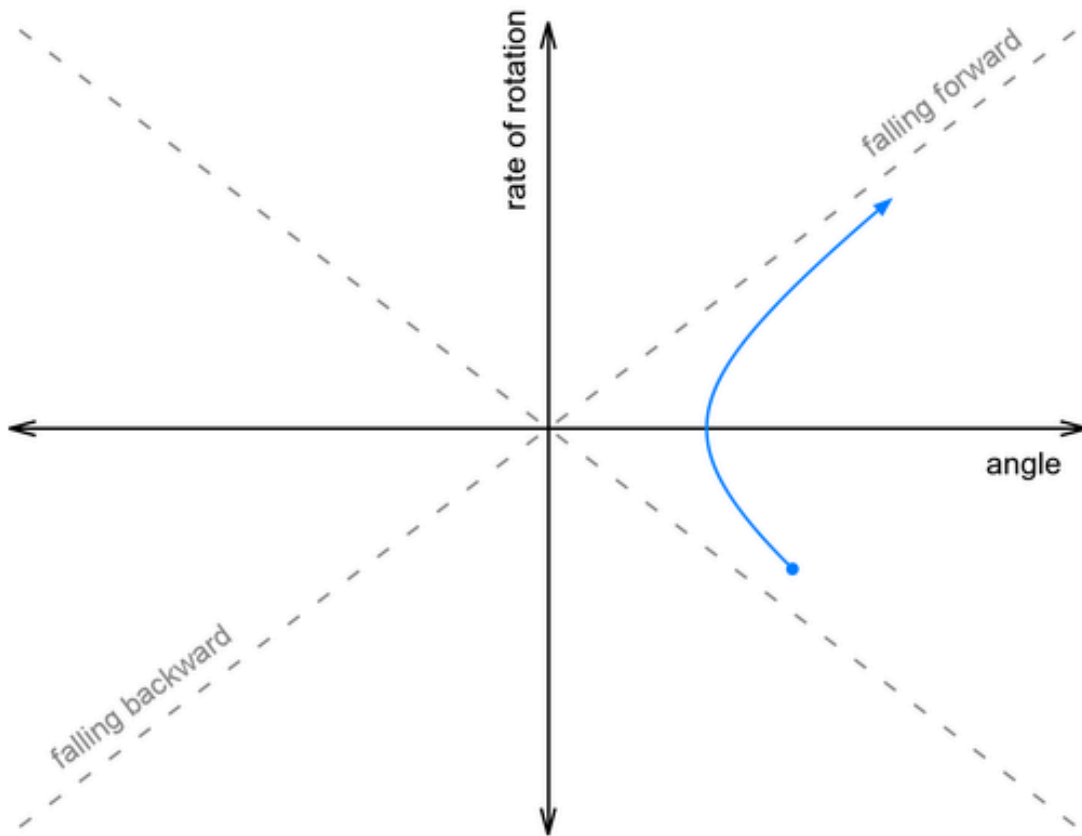


Angle convention used by the Balboa 32U4 balancing example.

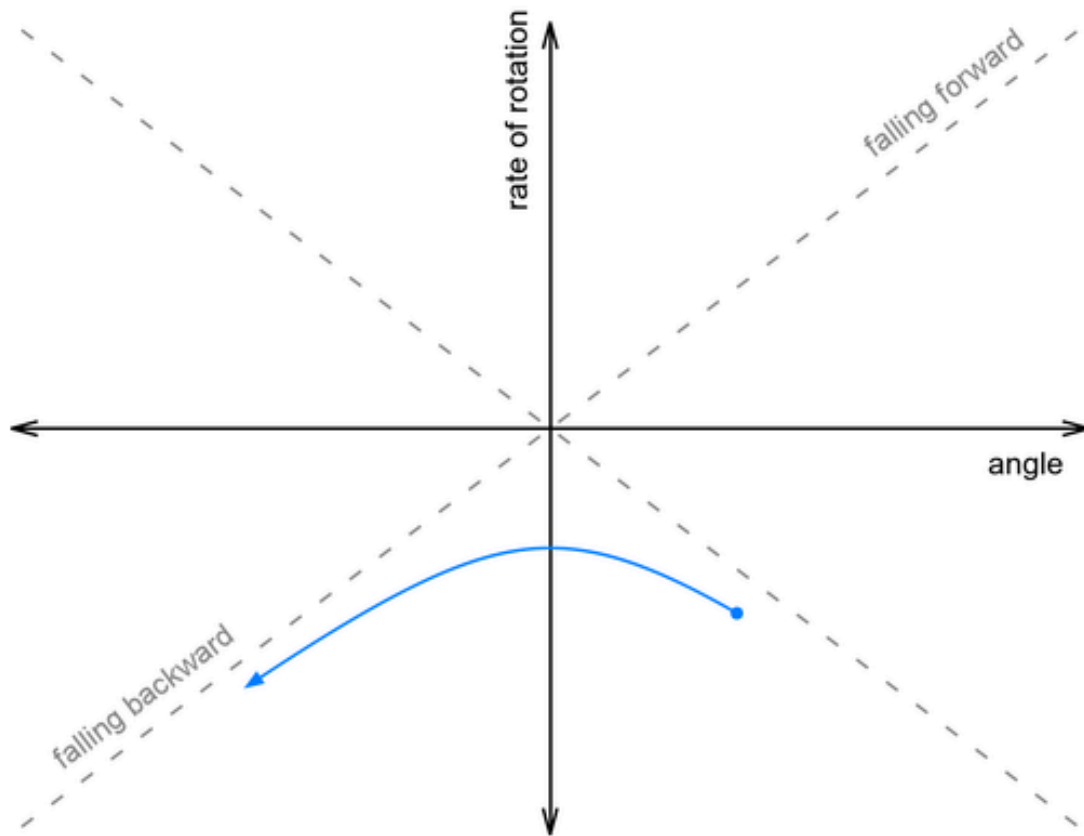
The gyro measurements we described in the previous section gave us two important variables:

- `angle` : the angle relative to vertical
- `angleRate` : the rate of rotation

When thinking about these variables, it is helpful to make a plot that shows the trajectory of the robot over time. Suppose we take a Balboa *with its motors off*, start it leaning forward, and give it a little push toward vertical. Initially, `angle` is positive and `angleRate` is negative. As the robot rises toward vertical, `angleRate` decreases until it runs out of momentum, stops, and starts falling forward. It continues to fall forward, faster and faster, until it hits the floor. The blue curve in the graph below shows approximately what the trajectory looks like:



Now suppose we push it harder, so that it falls over onto its other side. This time, it continues rotating as it passes through vertical, then falls backwards onto the floor:



Somewhere between these two paths lies a perfectly-balanced trajectory, indicated by the gray dashed line. If we could give it the exact right push, it would follow that line, rising up to vertical just as the rate of rotation falls to zero, and remain balanced forever.

This snippet of code from our **Balancer example project** [<https://github.com/pololu/balboa-32u4-arduino-library/tree/master/examples/Balancer>] computes how far off we are from this ideal rising trajectory:

```

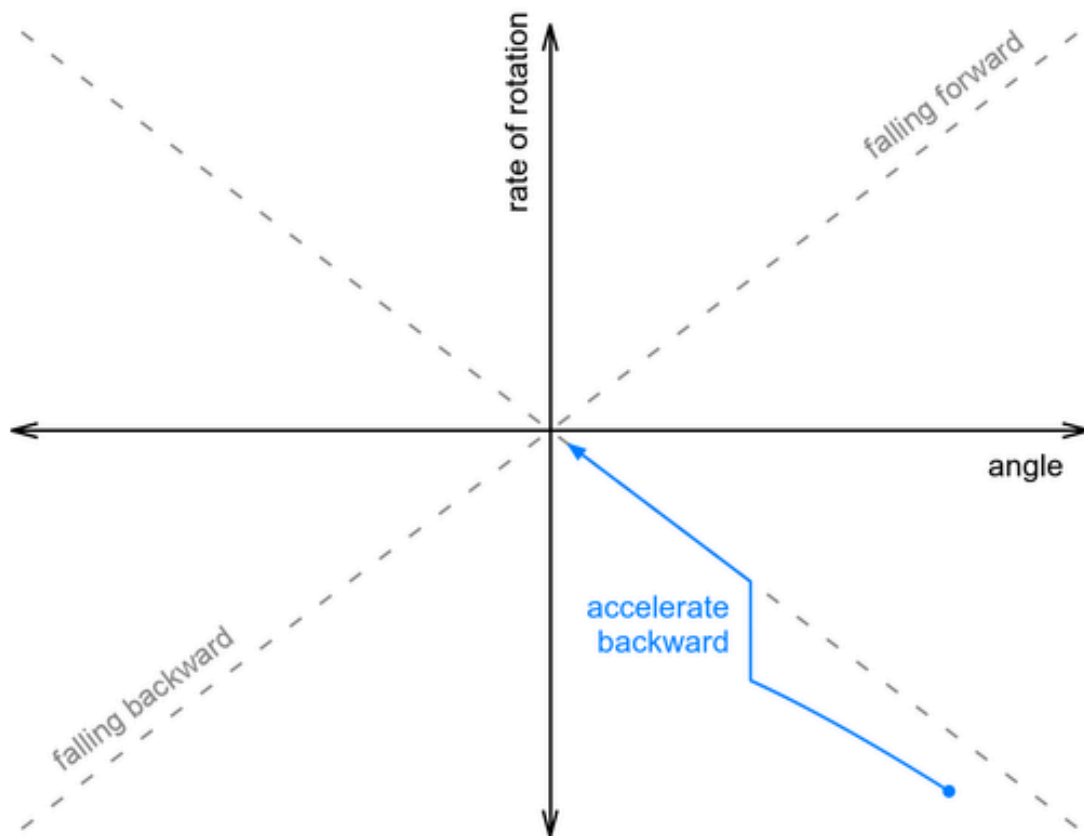
1 // This variable measures how close we are to our basic
2 // balancing goal - being on a trajectory that would cause us
3 // to rise up to the vertical position with zero speed left at
4 // the top. This is similar to the fallingAngleOffset used
5 // for LED feedback and a calibration procedure discussed at
6 // the end of Balancer.ino.
7 //
8 // It is in units of millidegrees, like the angle variable, and
9 // you can think of it as an angular estimate of how far off we
10 // are from being balanced.
11 int32_t risingAngleOffset = angleRate * ANGLE_RATE_RATIO + angle;

```

In the code, `ANGLE_RATE_RATIO` is a constant that must be determined through experiment. (A value of 140 worked well for the units we used and our Balboa's configuration.)

When a Balboa is actively balancing, it “pushes” itself by adjusting the speed of its motors. When the motors make a sudden change in speed, they give a push to the chassis (the combined effect of direct motor torque and of the horizontal motion of the wheels). The effect is the same as if you pushed the chassis by hand: the rate of rotation suddenly changes, in proportion to the change in motor speed.

If you think about it a little, you should see that applying *backwards* acceleration makes the rate of rotation *increase* (in the positive direction). So how could a Balboa on a trajectory like the one above save itself? It needs to apply just enough backwards acceleration to bump it up onto that ideal dashed gray line:



We don't know the exact relationship between acceleration and change in rate of rotation, and acceleration is not actually instantaneous, but the basic point is that we should adjust our motor speed by a factor proportional to the `risingAngleOffset` variable determined earlier. Here's approximately how we do that in our code:

```
1 | int32_t risingAngleOffset = angleRate * ANGLE_RATE_RATIO + angle;
2 | motorSpeed += ANGLE_RESPONSE * risingAngleOffset;
```

In this case `ANGLE_RESPONSE` is a constant that needs to be adjusted experimentally until the robot can

“catch” itself from a variety of starting conditions, ending up as vertical as possible.

But what happens after the robot catches itself? It reached a balanced position by changing the motor speed, so now the motors are driving off in some direction. It is balanced, so there is no reason for it to accelerate or decelerate, and it will drive away until it bumps into something or falls down, which is clearly not ideal behavior.

The Balboa 32U4 includes integrated quadrature encoders that allow a continuous measurement of how fast and far the wheels have turned. We can prevent the robot from driving away by adding additional adjustments to the motor speed that depend on the encoder readings. Counterintuitively, the way to stop it from driving away in one direction is to accelerate even faster in the same direction, causing it to fall back toward where you want to be. Two additional terms are enough to get it to come back to its starting point:

```
1 int32_t risingAngleOffset = angleRate * ANGLE_RATE_RATIO + angle;
2 motorSpeed += ANGLE_RESPONSE * risingAngleOffset
3   + DISTANCE_RESPONSE * distance
4   + SPEED_RESPONSE * speed;
```

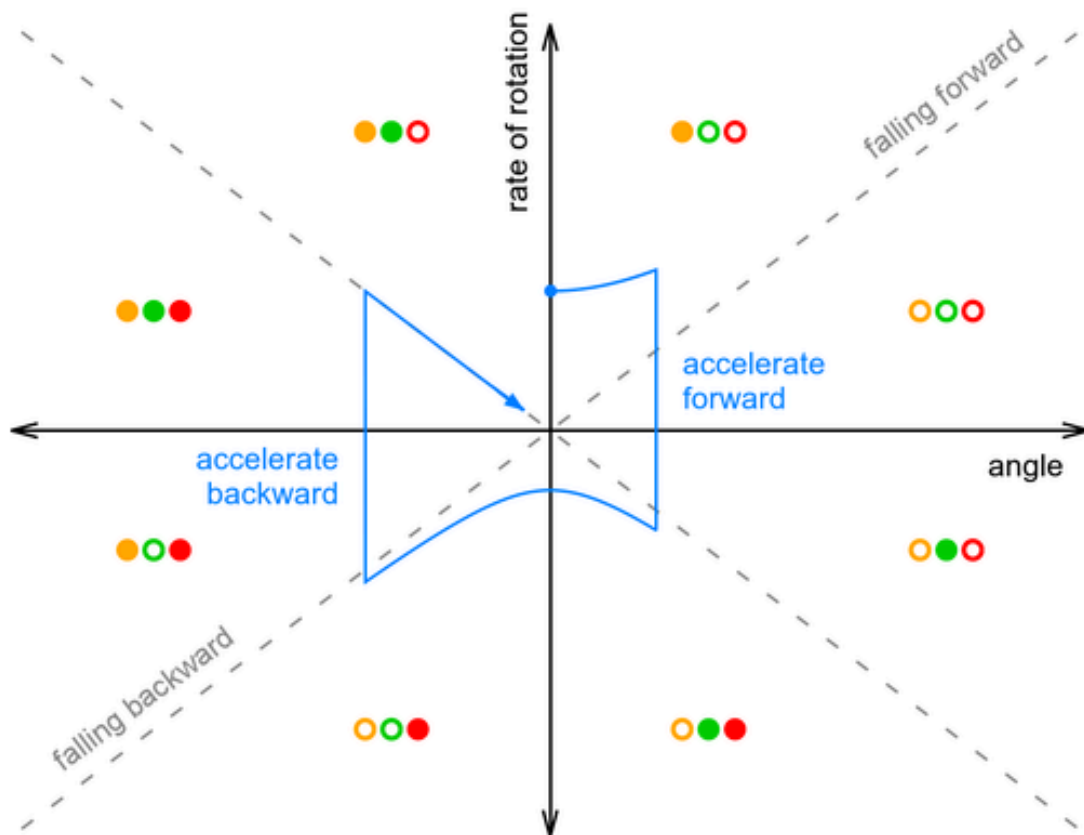
Here `distance` and `speed` are our encoder-based measurements of how far the robot is from its starting point and how fast it is going; each variable is multiplied by a constant that must be calibrated experimentally.

The final result is similar to a PID algorithm, but it responds to both rotational and translational motion with a single output, the motor speed. You can probably get similar results just by starting with the angle and distance variables, creating all six possible PID terms, and adjusting their constants to optimize the motion, but it can be hard to get so many constants right at the same time without a clear understanding of what each one means.

The following video shows our balancing algorithm in action. (We did not discuss how to make the robot get up from a lying-down position; see the example code for details.)

[<https://www.youtube.com/watch?v=WMTZy9QntLg>]

The yellow, green, and red LEDs visible in the second part of the video display what the Balboa thinks of its state, with each of the eight possible color combinations indicating a different eighth of the graph. The figure below shows the LED colors in each section of the graph along with the approximate trajectory of the robot after being pushed, so that you can try to follow along with the video:



One thing you can see from the graph is that the amount of forward acceleration and backward acceleration are about the same, so that overall effect is to drive forward then decelerate to a stop. It's also important to note that the graph makes it look like the robot only does two large corrections, while in reality it is constantly making small adjustments to the motor speed. Its actual trajectory might look like a smoothed-out version of the blue line, without sharp corners.

See **our Balancer example code** [<https://github.com/pololu/balboa-32u4-arduino-library/tree/master/examples/Balancer>] for more details and tips on calibration.

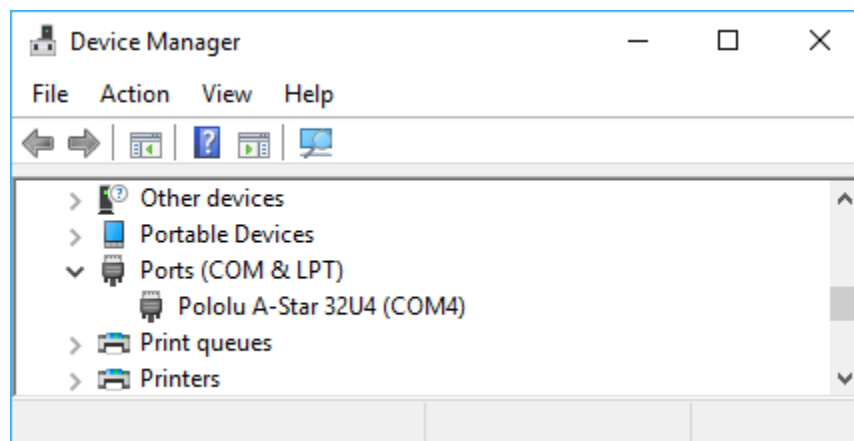
8. The Balboa 32U4 USB interface

Our 32U4 family of boards are based on a single ATmega32U4 AVR microcontroller that runs the user program and also handles the USB connection to the computer. The AVR has a full-speed USB transceiver built into it and can be programmed to present almost any type of USB device interface to the computer.

USB is an asymmetric system that consists of a single “host” connected to multiple “devices”. The host is typically a personal computer. The ATmega32U4 can only act as a USB device, so an A-Star device cannot be connected to other USB devices like mice and keyboards; it can only be connected to a host such as your computer.

Programming an ATmega32U4 board using the Arduino IDE as described earlier will automatically configure it as a composite device with a single virtual serial port. If you program the microcontroller with an Arduino sketch that implements another USB device class, like HID or MIDI, you will see additional child devices as well.

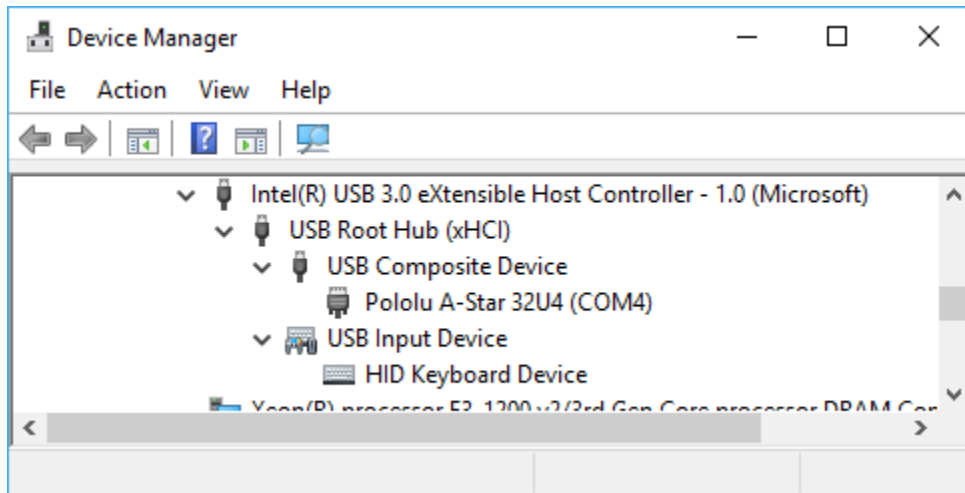
On a Windows computer, you can see the virtual serial port by going to your computer's Device Manager and expanding the “Ports (COM & LPT)” list. You should see a COM port labeled “Pololu A-Star 32U4”. In parentheses after the name, you will see the name of the port (e.g. “COM3” or “COM4”). Windows will assign a different COM port number to the device depending on what USB port you plug it into and whether it is in bootloader mode or not. If you need to change the COM port number assigned to the A-Star, you can do so using the Device Manager. Double-click on the COM port to open its properties dialog, and click the “Advanced...” button in the “Port Settings” tab. From this dialog you can change the COM port assigned to the device.



Windows 10 Device Manager showing the A-Star's virtual COM port.

On a Windows computer, you can see the rest of the USB interface by going to the Device Manager, selecting **View > Devices by connection**, and then expanding entries until you find the “Pololu A-Star

32U4" COM port. Near it, you should see the parent composite device.



The Windows 10 Device Manager in “Devices by connection” mode, showing that the A-Star is a composite device.

On a Linux computer, you can see details about the USB interface by running `lsusb -v -d 1fffb:` in a Terminal. The virtual serial port can be found by running `ls /dev/ttyACM*` in a Terminal.

On a Mac OS X computer, the virtual serial port can be found by running `ls /dev/tty.usbmodem*` in a Terminal.

You can send and receive bytes from the virtual serial port using any terminal program that supports serial ports. Some examples are the Serial Monitor in Arduino IDE, the **Pololu Serial Transmitter Utility** [<https://www.pololu.com/docs/0J23>], **Br@y Terminal** [<https://sites.google.com/site/terminalbpp/>], **PuTTY** [<https://www.chiark.greenend.org.uk/~sgtatham/putty/>], **TeraTerm** [<http://tssh2.osdn.jp/>], **Kermit** [<http://www.columbia.edu/kermit/ck80.html>], and **GNU Screen** [<http://www.gnu.org/software/screen/>]. Many computer programming environments also support sending and receiving bytes from a serial port.

9. The A-Star 32U4 Bootloader

Our 32U4 family of boards come with a USB bootloader that can be used in conjunction with the Arduino IDE or AVRDUDE to load new programs onto the device. This section documents some technical details of the bootloader for advanced users who want to better understand how it works. If you just want to get started using your device, it is fine to skip this section.

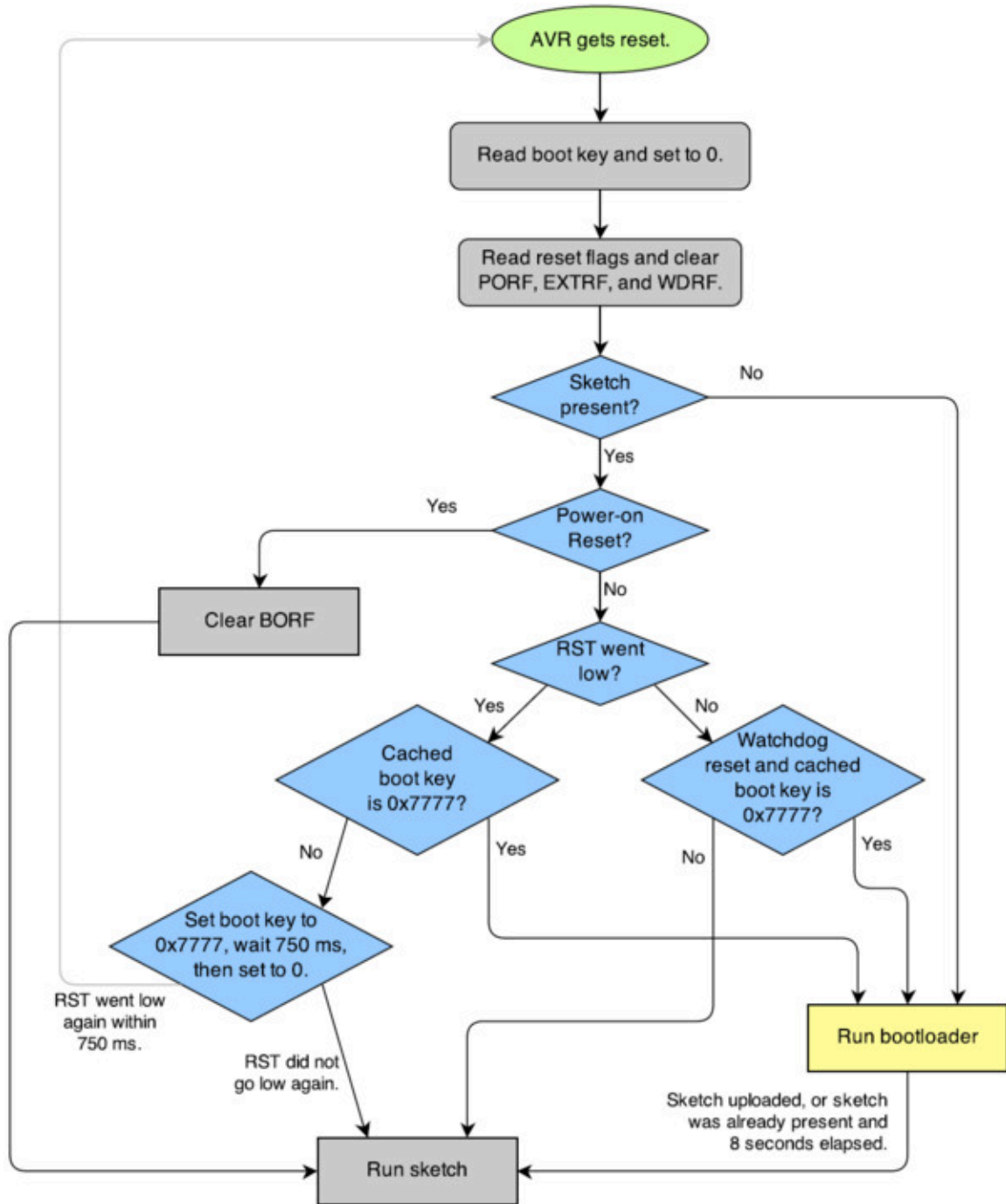
The A-Star 32U4 Bootloader is based on the **Caterina bootloader** [<https://github.com/arduino/Arduino/tree/master/hardware/arduino/avr/bootloaders/caterina>], which is the bootloader used on the **Arduino Leonardo** [<https://www.pololu.com/product/2192>], **Arduino Micro** [<https://www.pololu.com/product/2188>] and several other ATmega32U4 boards. The bootloader is open source and its **source code** [<https://github.com/pololu/a-star/tree/master/bootloaders/caterina>] is available on GitHub. The bootloader occupies the upper four kilobytes of the ATmega32U4's program memory, leaving 28 KB for the user program. The bootloader's USB interface consists of a single virtual serial port that accepts the programming commands defined in **AVR109** [<https://www.microchip.com/en-us/application-notes/an1644>]. The bootloader always runs first immediately after the AVR is reset.

Startup logic

The main difference between the A-Star 32U4 Bootloader and Caterina is in the startup logic. This is the part of the bootloader that runs immediately after the AVR is reset, and it decides whether to run the user program or run the rest of the bootloader. The startup logic of the Caterina bootloader is designed so that when the RST line goes low, the bootloader will run. This means that if you want to restart your program using the RST line, it will take 8 seconds before the bootloader times out waiting for an upload and the sketch starts.

The A-Star 32U4 Bootloader has different startup logic that allows you to use the RST line to reset the board with a smaller delay. If the RST line goes low once, the user program will run after a 750 ms delay. If the RST line goes low twice within 750 ms, then the bootloader will run. (This behavior is the same as on boards like SparkFun's Pro Micro.)

The start-up logic of the A-Star 32U4 Bootloader is shown in the flowchart below:



The startup logic for the A-Star 32U4 bootloader.

Brown-out detection

Unlike many other ATmega32U4 boards, our 32U4 family of boards have brown-out detection enabled. The brown-out threshold is 4.3 V, and if the voltage on VCC goes below this then the AVR will reset.

The bootloader was designed so that the user program can detect brown-out resets. To do so, check to see if the BORF bit in the MCUSR register is set, and then clear it later. Here is some example code you could put in your `setup` function for detecting brown-out resets:

```
1 pinMode(13, OUTPUT);
2 if (MCUSR & (1 << BORF))
3 {
4     // A brownout reset occurred. Blink the LED
5     // quickly for 2 seconds.
6     for(uint8_t i = 0; i < 10; i++)
7     {
8         digitalWrite(13, HIGH);
9         delay(100);
10        digitalWrite(13, LOW);
11        delay(100);
12    }
13 }
14 MCUSR = 0;
```

10. Reviving an unresponsive Balboa 32U4

In order to load a new program onto your A-Star 32U4 device, you will need to get it into bootloader mode and send programming commands to it over its virtual serial port using appropriate software. If you are programming the device from the Arduino IDE, the sketch loaded onto the device will generally support a special USB command for putting it in bootloader mode, and the Arduino IDE sends that command automatically when you click the Upload button. However, you might find yourself in a situation where the device is unresponsive and that method will not work. This can happen for two reasons:

- You accidentally loaded a malfunctioning program onto the device that is incapable of responding to the special USB command. For example, your program might be stuck in an infinite loop with interrupts disabled.
- You loaded a program which uses a non-standard type of USB interface or no USB interface.

The following sections provide different procedures you can use to revive your device.

10.1. Reviving using the Arduino IDE

This section explains two special methods for programming an A-Star (or another of our 32U4 family of boards) using the Arduino IDE in case your usual method of programming is not working. These instructions were developed for the Arduino IDE versions 1.0.5-r2 and 1.6.0, and they might need to be modified for future versions.

Reset button

If you have an A-Star 32U4 Micro, you should connect a **momentary pushbutton** [<https://www.pololu.com/product/1400>] between the GND and RST pins to serve as a reset button. Other boards in our 32U4 family have a reset button you can use. Alternatively, you can use a wire to temporarily connect GND and RST together instead of using a reset button.

Resetting the board twice within 750 ms makes the board go into bootloader mode. The bootloader will exit after 8 seconds and try to run the sketch again if it has not started receiving programming commands. To revive the device, you need to make sure you start sending it programming commands before the 8-second period is over.

In bootloader mode, the yellow LED (the one labeled *LED 13*) fades in and out. It is useful to look at this LED so you can know what mode the microcontroller is in. Also, we recommend enabling verbose output during upload using the Arduino IDE's "Preferences" dialog. Looking at the LED and looking at the verbose output during the following procedures will help you understand what is going on.

The uploading-before-bootloader method

The goal of the uploading-before-bootloader method is to select a non-existent serial port in the Arduino IDE and then make sure the Arduino IDE enters the uploading phase before the microcontroller goes into bootloader mode. This method has been tested on Arduino 1.0.5-r2 and 1.6.0. This method does not work on Arduino 1.5.6-r2 or Arduino 2.0.0 because those versions of the IDE gives a fatal error message if the selected serial port is not present at the beginning of the uploading phase (e.g. “Board at COM7 is not available.” or “Upload error: Failed uploading: no upload port provided”).

1. Connect the device to your computer via USB.
2. In the “Tools” menu, open the “Board” sub-menu, and select “Pololu A-Star 32U4”.
3. In the “Tools” menu, open the “Port” sub-menu, and check to see if any ports are selected. If the “Port” menu is grayed out or no ports in it are selected, that is good, and you can skip to step 6.
4. Reset the board twice to get the board into bootloader mode. While the board is in bootloader mode, quickly select the new serial port that corresponds to the bootloader in the “Port” menu.
5. After 8 seconds, the bootloader will exit and attempt to run the sketch again. Wait for the bootloader to exit. Verify that either the “Port” menu is grayed out or no ports in it are selected.
6. Click the Upload button. The Arduino IDE will compile your sketch and start uploading it.
7. As soon as the large status bar near the bottom of the IDE says “Uploading...”, reset the board twice to get into bootloader mode.

The Arduino IDE will stay in the uploading phase for 10 seconds, waiting for a new serial port to appear. Once the serial port of the bootloader appears, the Arduino IDE will connect to it and send programming commands.

The bootloader-before-uploading method

The goal of the bootloader-before-uploading method is to select the bootloader’s virtual serial port in the Arduino IDE and then make sure the board is in bootloader mode at the time when the Arduino IDE enters the uploading phase.

1. Connect the device to your computer via USB.
2. In the “Tools” menu, open the “Board” sub-menu and check to see if the “Pololu A-Star 32U4 (bootloader port)” entry is visible. If this entry is visible, you can skip to step 6.
3. Using a text editor, open the file named boards.txt that provides the “Pololu A-Star” board entries. In Windows, you can typically find this file in `%LocalAppData%\Arduino15\`

`packages\pololu-a-star\hardware\avr\`. In Linux, you can typically find this file in `~/.arduino15/packages/pololu-a-star/hardware/avr/`. On macOS, you can typically find this file in `~/Library/Arduino15/packages/pololu-a-star/hardware/avr/`. If you installed the boards manually instead of using the Board Manager, you can find it in **[sketchbook location]/hardware/pololu/avr**.

4. In the `boards.txt` file that you opened, find the lines at the bottom of the file that start with `#a-star32U4bp`. Uncomment each of those lines by deleting the “#” character, and then save the file.
5. Close the Arduino IDE and restart it.
6. In the “Tools” menu, open the “Board” sub-menu and select “Pololu A-Star 32U4 (bootloader port)”. This entry is configured so that the Arduino IDE will send programming commands directly to selected serial port, instead of trying to send a special USB command to the port to get it into bootloader mode and then waiting for the new port to appear. By selecting this entry, the timing of the programming process below becomes easier, especially on Windows.
7. Prepare the computer to show you a list of its virtual serial ports. If you are using Windows, this means you should open the Device Manager. If you are on Linux or macOS, this means you should open a Terminal and type the command `ls /dev/tty*` but do not press enter until the board is in bootloader mode in the next step.
8. Reset the board twice to get the board into bootloader mode. While it is in bootloader mode, quickly look at the list of serial ports provided by your operating system in order to determine what port the bootloader is assigned to.
9. Reset the board twice to get the board into bootloader mode again. While the board is in bootloader mode, quickly select the serial port of the bootloader in the Arduino IDE. The port can be selected in the “Port” sub-menu under “Tools”.
10. In the Arduino IDE, click the “Verify” button to compile your sketch. This could make the timing easier during the next step.
11. Press the reset button twice to get the board into bootloader mode again. As soon as you see the yellow LED fading in and out, press the Upload button.

The Arduino IDE will compile your sketch and then upload it to the selected serial port.

If the compilation of the sketch takes longer than 8 seconds, then this procedure will fail because the bootloader will time out and start trying to run the malfunctioning sketch again. If that happens, try the procedure again using a simpler sketch such as the Blink example that can be found under **File > Examples > 01.Basics > Blink**.

After reviving your device, be sure to change the Board setting back to “Pololu A-Star 32U4” and select the right Port.

10.2. Reviving using AVRDUDE

This section explains a special method for reviving an A-Star (or another of our 32U4 family of boards) using the command-line utility **AVRDUDE** [<http://www.nongnu.org/avrdude/>] in case your usual method of programming is not working. AVRDUDE stands for “AVR Downloader/UplodaDEr”, and it is compatible with the A-Star bootloader.

If you have an A-Star 32U4 Micro, you should connect a **momentary pushbutton** [<https://www.pololu.com/product/1400>] between the GND and RST pins to serve as a reset button. Other boards in our 32U4 family have a reset button you can use. Alternatively, you can use a wire to temporarily connect GND and RST together instead of using a reset button.

1. Connect the device to your computer via USB.
2. Prepare the computer to show you a list of its virtual serial ports. If you are using Windows, this means you should open the Device Manager. If you are on Linux or Mac OS X, this means you should open a Terminal and type the command `ls /dev/tty*` but do not press enter until the board is in bootloader mode in the next step.
3. Press the reset button twice within 750 ms to make the AVR go into bootloader mode. You should see the yellow LED fading in and out when the AVR is in bootloader mode. While it is in bootloader mode, quickly look at the list of serial ports provided by your operating system in order to determine what port the bootloader is assigned to.
4. Type the following command in your terminal and replace COM4 with the name of the bootloader's serial port, but do not press enter yet. This command will erase the malfunctioning program on the device but preserve the bootloader.

```
avrdude -c avr109 -p atmega32U4 -P COM4 -e
```

5. Press the reset button twice within 750 ms to make the AVR go into bootloader mode.
6. Quickly run the command you typed previously. The command needs to be run within 8 seconds of starting the bootloader, or else the bootloader will exit and try to run the malfunctioning program again.

By following the instructions above, the malfunctioning program on the device will be erased and the device will stay in bootloader mode indefinitely. You can now load another program onto it using the Arduino IDE or AVRDUDE.

11. Related resources

To learn more about using the Balboa 32U4, see the following list of resources:

- The Arduino IDE has many **examples** [<http://arduino.cc/en/Tutorial/HomePage>] that can run on the Balboa 32U4 (although note that the control board's on-board hardware might conflict with some of these examples).
- The Arduino website has a **Language Reference** [<http://arduino.cc/en/Reference/HomePage>], a wiki called the **The Arduino Playground** [<http://playground.arduino.cc/>], and other resources.
- The Balboa 32U4 control board uses the same microcontroller as the **Arduino Leonardo** [<https://www.pololu.com/product/2192>] and **Arduino Micro** [<https://www.pololu.com/product/2188>], so you can search the Internet for relevant projects and code examples that use one of those boards.
- **Atmel's ATmega32U4 documentation** [<https://www.microchip.com/en-us/product/ATmega32u4>] has the ATmega32U4 datasheet and many related documents.
- **AVR Libc Home Page** [<http://www.nongnu.org/avr-libc/>]: this page documents the standard library of functions that you can use with GNU C and C++ compilers for the AVR.
- **Balboa 32U4 Arduino library** [<https://github.com/pololu/balboa-32u4-arduino-library>]
- **Balboa 32U4 library documentation** [<https://pololu.github.io/balboa-32u4-arduino-library/>]
- **LUFA – the Lightweight USB Framework for AVRs** [<http://www.fourwalledcubicle.com/LUFA.php>]
- **WinAVR** [<http://winavr.sourceforge.net/>]
- **Microchip Studio for AVR and SAM Devices** [<https://www.microchip.com/en-us/tools-resources/develop/microchip-studio>]
- **AVRDUDE** [<http://www.nongnu.org/avrdude/>]
- **AVR Freaks** [<https://www.avrfreaks.net/>]

Datasheets for some of the components found on the Balboa 32U4 control board are available below:

- **ATmega32U4 documentation** [<https://www.microchip.com/en-us/product/ATmega32u4>]
- **Texas Instruments DRV8838 motor driver datasheet** [<https://www.pololu.com/file/0J806/drv8838.pdf.redirect>] (1k redirect)
- **ST LSM6DS33 3D accelerometer and 3D gyro module datasheet** [<https://www.pololu.com/file/0J1087/LSM6DS33.pdf>] (1MB pdf)
- **ST LIS3MDL 3-axis magnetometer datasheet** [<https://www.pololu.com/file/0J1089/LIS3MDL.pdf>]

(2MB pdf)

- **Texas Instruments TPS2113A power multiplexer datasheet** [<https://www.pololu.com/file/0J771/tps2113a.pdf.redirect>] (1k redirect)

Finally, we would like to hear your comments and questions on the **Pololu Robotics Forum** [<https://forum.pololu.com/>]!