An Electronic Compass for Small Autonomous Robots

by

Matthew J. Marjanović

Submitted to the Department of Physics
in partial fulfillment of the requirements for the degree of

Bachelor of Science

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

February 1993

Author ....
Department of Physics
January 15, 1993

Certified by ....
Rodney A. Brooks
Associate Professor, EECS Department
Thesis Supervisor

Accepted by ....
Aron M. Bernstein
Undergraduate Thesis Coordinator, Physics Department

An Electronic Compass for Small Autonomous Robots

by

Matthew J. Marjanović

Submitted to the Department of Physics
on January 15, 1993, in partial fulfillment of the
requirements for the degree of
Bachelor of Science

Abstract

This thesis report describes the design of an electronic compass intended for use as a sensor on autonomous mobile robots. The sensor uses Hall effect devices to measure two perpendicular components of the Earth's magnetic field, producing a pair of analog output signals. The signals are fed into analog-to-digital conversion [ADC] ports on a robot, allowing software to calculate the heading. Such software was written for the Motorola 68HC11 microprocessor, the predominant processor in use at the MIT Mobile Robotics Laboratory, where this compass was developed. Although the angular resolution of the software is 1.5°, noise in the sensors limits the precision of the compass to ±1.7°.

Using surface mount electronics, the sensor fits within a $1\frac{1}{8}''$ cube. It requires a power supply of 5 volts at 70 mA. The compass as built is a two-axis device, and must be held parallel to the ground to operate accurately. However, the design can easily be expanded to a three-axis device which will operate in any orientation.

Thesis Supervisor: Rodney A. Brooks
Title: Associate Professor, EECS Department

Acknowledgments

Here's thanks to all the folks I'd like to thank:
(This is just like the back of the CD liner notes.)

Maja for getting me hooked on Mobots; Rod for saying "Go ahead;" James McLurkin for suggesting compasses way back in the summer; Dave Barrett for discouraging the fish for the time-being; the Helicopter Gang; Mike Bolotski 'cause he's such a nice guy; Mike Connell 'cause we are the meisters.

the whole Pecker gang, with particulars to Upe and Pat for proofreading (pillaging is more like it), Lisa for being in tune (good luck to her daddy), Hoang for being out of tune, Bosco because he's boschamatic, Multimedia Evan for getting to the point, TutorEvan for missing the point but my he has a fine voice, Steve and Zwink his blanket, Zip until frisbee season returns, Lumpy for the cleats and spaghetti, Ming for diligent caretaking of the soda fridge, Capalbo for setting the scales, Jim for playing xconq and then bragging about it because that's just the kind of guy he is, the Freshmen – Mark, Christian, and James – for the hours of family fun, the Freshwomen – I think it's just Karen and Marsha – for being so goofy, geez;

hey, and the Old Guard Peckers, too, Willy the original Nadley, Mac the spiffy dresser, Russell my mentor, even Vi in MedSchool, Akbar from way back because he also set the scales, Vince powerman, Simon the big galoot, Robby who had a ROTC girlfriend, hey and Mr. Mungan too who is still in town.

and then the family... Mom, and Tash – Tash being Natasha my sister who has agreed to split the world in half with me, but I forgot which half I get, Kari, Dominic, Lisa, Andrew in chronological order (man, am I exhausted), the two Tetas – Silva and Liza – and the uncles, Kevin and Knut (two K's, never noticed that before.) and Baka, and Dedo, who died two months too soon to see this but he knew it was coming, and if anyone did, he's the one who got me here,
where I am today.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

For my undergraduate thesis project, I have designed an electronic compass package for use on small, autonomous robots, particularly those based on the Motorola 68HC11 microprocessor. The package consists of a sensor which measures the Earth's magnetic field, and a piece of software which converts those measurements into a heading. The software is written for the 68HC11, but the sensor itself can be used on any robot which has free analog-to-digital conversion ports.

This report is divided into four main parts:

Design Philosophy – a discussion of the motivations behind this project, and the rationale behind the basic design

The Hardware – a description of the sensor electronics

The Software – an explanation of heading calculation and the compass software

The Prototype – a discussion of the performance of a prototype unit, including a description of the calibration procedure

Appendices containing the schematics, parts list, and software listing for the prototype are included at the end of this report.

Chapter 2

Design Philosophy

2.1 Motivation

My original idea for a thesis project was to build a fish, an autonomous aquatic robot. I decided that the fish should have a compass as one of its many sensors. After checking around the lab, I realized that none of the working robots at the Mobot Lab had a compass, though many could use one.

A background search revealed two commercially available options. One was to buy a ready-made compass module from a company such as KVH Industries. The other was to reverse-engineer a sensor by removing the analog board from a digital automobile compass, such as those made by Zemco. Both choices result in a bulky sensor (at least $1'' \times 2'' \times 3''$) with difficulties in either finding a power supply or interfacing to a robot. The ready-made modules are also unnecessarily accurate and expensive.

What the lab needed was a small, inexpensive, easy-to-interface compass sensor that could be added to any robot as an afterthought. So, I put the fish idea on a backburner and decided to make a compass instead.

The compass I have designed is tailored for use on the IS Robotics R1 robot,[1] although the hardware and software can be immediately ported to any robot which uses a Motorola 68HC11 microprocessor. The compass works by producing two analog output signals proportional to two perpendicular components of the Earth's magnetic field in the horizontal plane. These signals are fed into a 68HC11 on the R1 through analog-to-digital conversion (ADC) ports on the chip. A short software routine which I have written converts the data to a heading angle. With new software, the sensor can be interfaced to any robot which has two free ADC ports.

[1] The R1 was chosen because its operation relies on a global positioning system which, unfortunately, does not directly provide heading or orientation information.

2.2 Design Constraints

The R1 robot is an ideal vehicle for this compass; if the compass can work on an R1, it will work just about anywhere else. Functioning on an R1 imposes the following constraints:

Size and Weight The R1 is a small truck-like robot with a 5"x12" footprint. The R1 is also ridiculously mechanically deficient, so any sensor mounted on it needs to be small and lightweight. My goal was a compass which fits within a 1" cube and weighs under 3 ounces. Such a device can be easily carried by any of the other robots used in the Mobot Lab, including the R2 (the successor to the R1), and Atilla and Genghis (two of the six-legged walking robots).

Power Supply The power bus on the R1 is a +5 volt supply, sourced by nickel-cadmium rechargeable batteries. Thus, the compass must operate from a single-ended +5 volt supply. My aim was to keep the operating current under 25 milliamperes.

Output The outputs must run between 0 and 5 volts, the input range of the ADC ports on a 68HC11.

Accuracy and Precision The mechanical deficiencies of the R1 allow some leeway in this category. The current software on the R1 robot designates a heading as one of only 16 different directions, so any accuracy to better than $\pm 11°$ is sufficient. I wanted to obtain better than $\pm 5°$ precision and accuracy.

Cost The Mobot Lab has twenty R1's, so the compass needed to be cheap and easy to make. The target cost for the compass was $50 each, the price of an off-the-shelf Zemco compass.

The result of working under these constraints is a small, sturdy device which uses several high-performance integrated circuits, all of which are available in surface mount packaging.

2.3 Magnetic Field Detection Options

An electronic compass is essentially a gaussmeter sensitive enough to measure the Earth's magnetic field, on the order of $\frac{1}{2}$ gauss. Out of the 1,001 techniques available for measuring magnetic fields, two are immediately applicable to the electronic compass: fluxgate magnetometry and Hall effect sensing.

2.3.1 Fluxgate Magnetometers

A fluxgate magnetometer, in the configuration found in commercial compasses, is composed of three coils wound around a ring of magnetic material (Figure 2-1). Two perpendicularly wound coils are the x and y component sense coils, and a toroidally wound coil provides the drive signal for the ring, or fluxgate. The ring has an exceptionally high initial permeability ($\mu > 200,000$) which saturates at very low fields.[Bolt., p. 21ff]

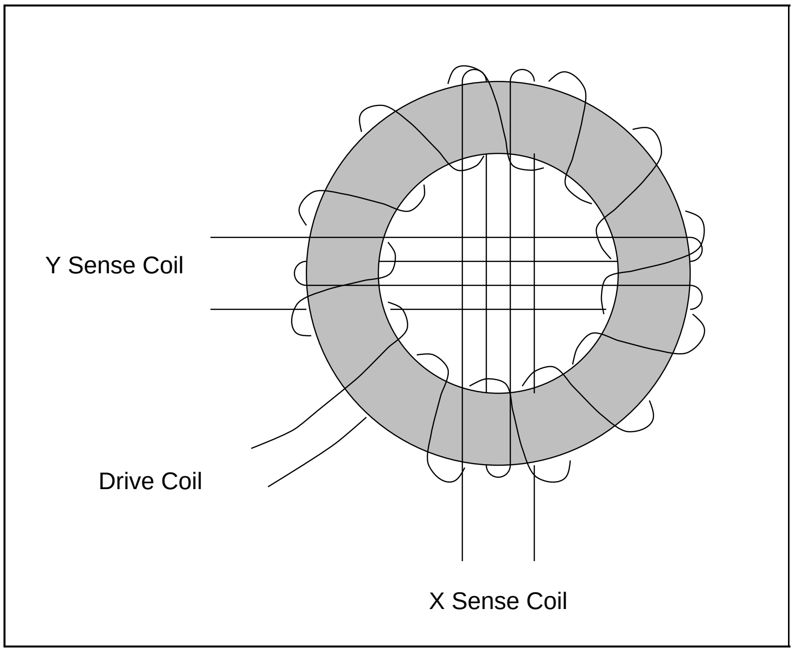

Figure 2-1: Typical configuration of a fluxgate magnetometer sensor.

To illustrate the operation of the fluxgate, consider a single sense coil in the absence of an external field. When an oscillating current is applied to the drive coil, an oscillating flux is produced in the ring. The ring is repeatedly driven into saturation, and the magnetic flux looks like a square wave in time. The sense coil intersects the ring in two places, and the flux through the cross-sections flows equally in opposite directions. The net flux encompassed by the sense coil is zero, so the sense signal is zero.

If an external magnetic field is introduced perpendicular to the sense coil, one side of the ring will saturate slightly before the other. During the delay, the flux through the two cross-sections will not cancel, and the sense coil will detect a small spike with every oscillation of the drive coil. This signal is integrated and fed back as a DC current into the sense coil to cancel the external field. The size of the current determines the field strength. Since the field in the ring is held to nearly zero by the feedback, the fluxgate magnetometer is insensitive to the exact magnetic properties of the ring, as long as the ring is uniform.

By using two perpendicular sense coils, two quadrature outputs are obtained, one for each horizontal component of the field.

2.3.2 Hall Effect Sensors

Hall effect sensors utilize the Hall effect, a phenomenon which manifests itself to different degrees in all conductors. To understand the Hall effect, imagine a block of conductive material carrying a current (Figure 2-2). Assume the charge carriers are electrons. If the block is placed in a magnetic field, the Lorentz force on the electrons will push them in a direction perpendicular to both the field and direction of current flow. The shift in the charge distribution creates a small potential difference across the block, proportional to both the current and the strength of the field.[Grif., p. 241] If the current is fixed, the differential voltage across the block will give a measurement of the magnetic field.

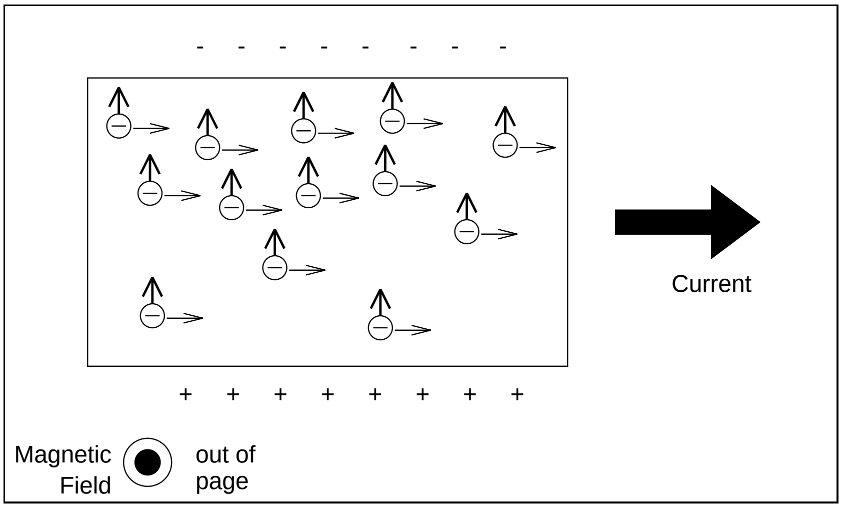

Figure 2-2: The Hall effect in a generic conductor.

A Hall effect sensor is nothing more than a block of conducting material with four leads attached to it. The composition of the conductor is very important in determining the magnitude of the Hall voltage; most commercial Hall effect sensors are made of a semiconductor such as indium-arsenide (InAs) or gallium-arsenide (GaAs).[Bell, pp. 2-4]

All of the commercial electronic compasses that I have encountered, such as the Zemco compass, use fluxgate technology. I chose to use Hall effect sensors despite several disadvantages they have in comparison to fluxgate sensors. At gauss-size fields, the Hall voltage is pretty small, usually in the microvolt range. To obtain any useful sensitivity, it is necessary to use either large control currents (upwards of 200 mA for some devices), or efficient but noisy semiconductor compositions, such as GaAs. Hall devices also have temperature sensitive gains and offset voltages. The fluxgate magnetometer, with its null-feedback design, is comparatively stable and noise-free.

One limitation of fluxgate magnetometers, however, is that they are planar, two-axis devices. A fluxgate compass must always be held parallel to the ground so that it reports a heading which is along the ground and not into it. Hall effect sensors are small, and in the same physical volume as a two-axis fluxgate device, one can fit a three-axis Hall effect compass and inclinometers to give pitch and roll information. With this data, a robot can compute the direction of the complete magnetic field vector and then project it onto the horizontal plane mathematically.

Recall that my original idea was to put this compass into a fish, which could conceivably turn in any direction.[2] No gimble mount, as used in the some commercial compasses, will give this amount of freedom. For this thesis, I have designed a simpler two-axis version of the compass, which has an immediate application to the R1 robots. The R1's can only travel in the horizontal plane, if they travel at all, so a third axis of measurement is not necessary. Adding that third axis to the design later amounts to nothing more than adding another Hall effect sensor and duplicate channel of amplification.

[2] Atilla and Genghis, the all-terrain robots at the Mobot Lab, would also be happier with 3-dimensional compasses.

Chapter 3

The Hardware

The compass hardware is composed of a sensor head and a printed circuit board containing a power supply and two identical amplifier circuits (Figure 3-1). The power supply provides a regulated 8 volts for two Hall effect devices in the sensor head, and the amplifiers boost the Hall output to a level which can be processed by a 68HC11.

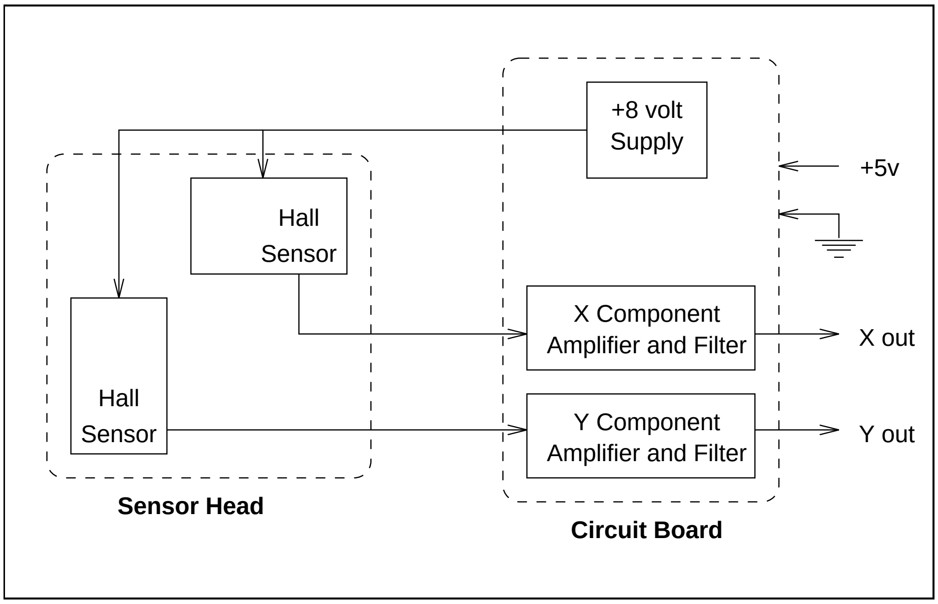

Figure 3-1: Block diagram of the compass hardware.

3.1 Sensor Head

The sensor head is depicted in Figure 3-2. Two MicroSwitch SS94A1F Hall effect sensors are held perpendicular to each other in a block of Delrin plastic.[1] Each Hall effect device is flanked by slugs of a ferrite material which improve the sensor response.

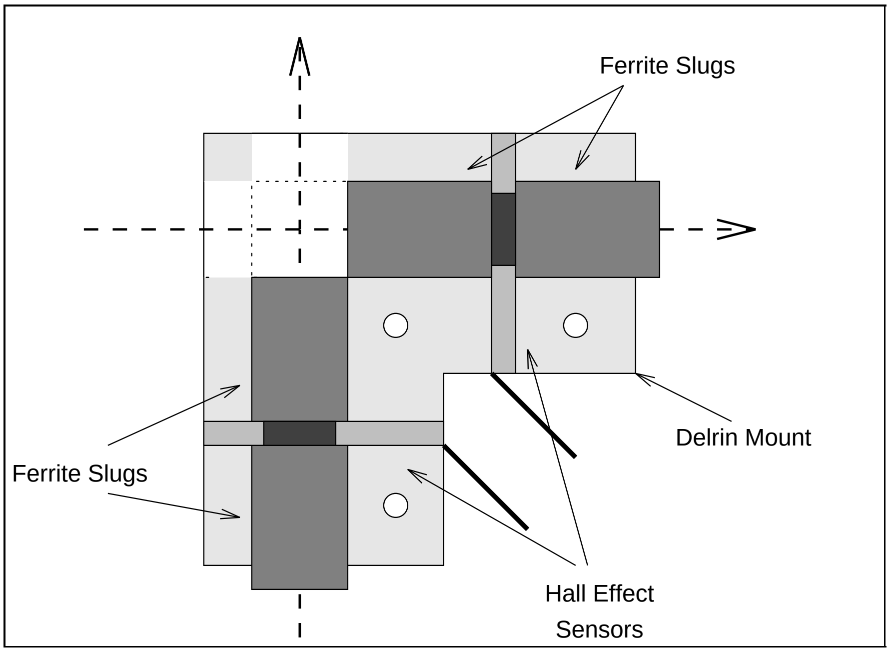

Figure 3-2: The compass sensor head.

3.1.1 Choice of Hall Sensor

I considered four varieties of Hall effect devices for this project: the F.W. Bell FH-540 and GH-600, the Allegro UGS-3503, and the MicroSwitch SS94A1F. The first two are basic four-lead Hall effect devices, with two leads to supply the control current and two to measure the differential Hall voltage. The last two models are integrated sensors containing a Hall device and an onboard amplifier.

The four-lead devices are attractive because they are very small — the FH-540 is just a tiny .135"x.100"x.025". However, these devices require current sources to drive them and high gain instrumentation amplifiers to extract a useful signal. Each model also suffers from its own particular drawback. The sensitivity of the FH-540 is roughly 12 $\mu V/gauss$, yet its null (zero-field) voltage drifts by up to 10 $\mu V/°C$. If you breathe on it, the signal is swamped. The GH-600 is more field sensitive ($50 - 140$ $\mu V/gauss$) and less temperature sensitive (under 0.6 $\mu V/°C$). It is also quite noisy. In early trials, peak-to-peak flicker from this sensor amounted to $67\mu V$ on a $167\mu V$ signal.

The integrated Hall sensors require less external amplification, are less noisy, and are more

[1] Any non-ferrous material could be used; Delrin was chosen because it is common and easy to machine.

temperature stable. The UGS-3503 is designed to operate from a +5 volt supply and generates 1.3 $mV/gauss$. The SS94A1F has a tremendous response of 25 $mV/gauss$, and is temperature compensated with laser trimmed resistors on the chip itself, yielding a null drift of under $0.1\%/°C$. However, the SS94A1F requires an +8 volt supply.

The winner among the four contenders is the SS94A1F. Although it requires extra circuitry for the 8 volt supply, the high-sensitivity is unrivaled. Even more important is the factory adjusted on-chip temperature compensation, which would be very difficult to duplicate with discrete components.

3.1.2 Ferrite Slugs

The ferrite slugs surrounding each Hall sensor serve two purposes. First, they act as "flux concentrators." The Earth's field between the slugs is multiplied by the effective permeablility of the system, which depends on the geometry of the slugs. Although this effective permeablility is only a fraction of the intrinsic permeablility of the material, they still magnify the magnetic field passing through the Hall sensors by approximately a factor of 5. Consequently, the total amplifier gain can be reduced by the same factor, improving the signal-to-noise ratio and reducing the impact of offset drift.

The ferrite slugs also act as averaging devices. When sandwiched between them, the Hall effect sensor responds to the field along the length of the slugs, not just to the field present within the sensor's own thickness. This improves the compass' immunity to any local contortions of the Earth's magnetic field.

3.2 Power Supply

The SS94A1F sensor requires an +8 volt supply, outlined in Figure 3-3. The +5 volt compass supply is boosted to +10 volts by a Maxim MAX660 used in a voltage-doubler configuration. This 10 volts is then pared down to 8 volts by a standard LM317 regulator.

The MAX660 is a charge-pump voltage inverter/doubler chip which requires only three external components: two capacitors and a start-up diode. In this circuit the chip is set to operate in a high frequency mode, at 45 kHz rather than 5 kHz. This allows for the use of smaller capacitor values (and thus more compact capacitors) with the same output ripple, at the expense of a small increase in supply current.

3.3 Amplification

The compass has two identical amplifier circuits, one for each Hall sensor, shown in Figure 3-4. These circuits have three stages: a variable high-gain amplifier with coarse DC offset adjustment, a

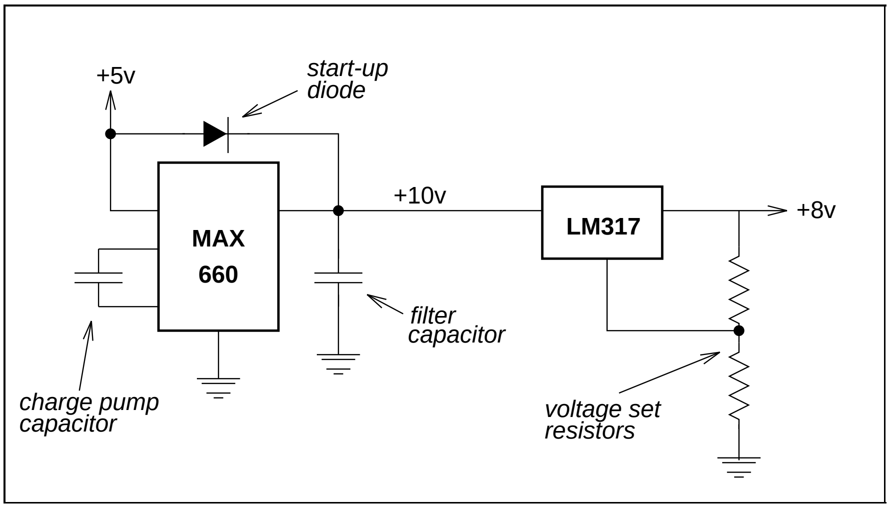

Figure 3-3: The +8 volt supply circuit

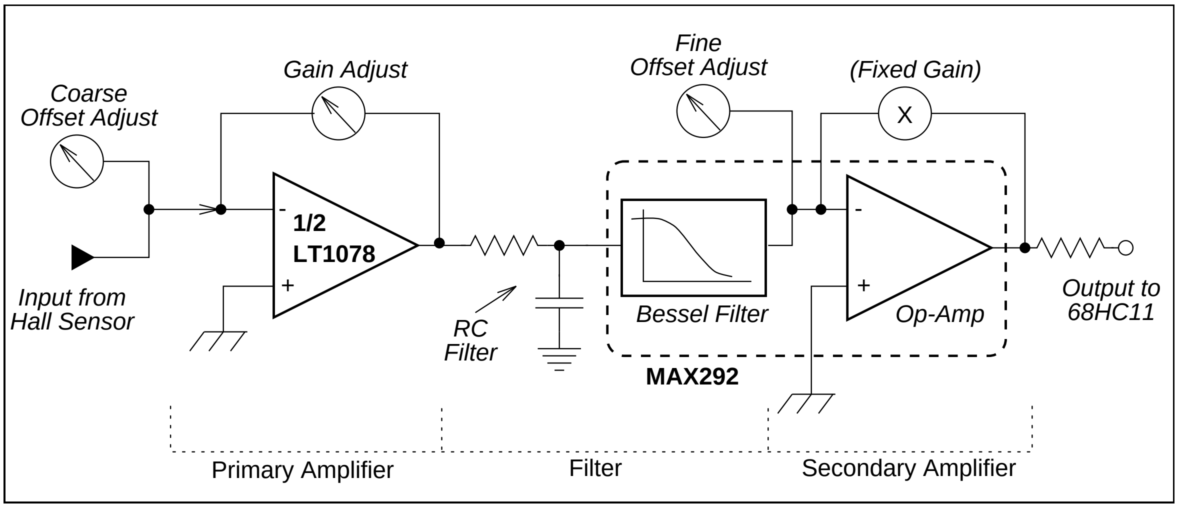

Figure 3-4: One of the two duplicate amplifier circuits

filter to reduce noise and limit the compass response, and a fixed low-gain amplifier with fine DC offset adjustment. Since these amplifiers are powered by a single-sided 5 volt supply, a resistive voltage divider is used to provide a 2.5 volt “ground” reference.

3.3.1 Primary Amplifier

The first stage is an inverting/summing amplifier. The output of the SS94A1F Hall effect sensor is centered about 4 volts, half of the sensor supply voltage, but the center voltage for the rest of the circuitry is 2.5 volts. So, an adjustable offset voltage is added to the sensor output to shift it down. An inverting amplifier configuration is ideal for this: since the inverting input to the amplifier becomes a virtual ground (or, rather, a virtual 2.5 volt source) the common-mode range of the op-amp is never exceeded. The gain of the amplifier can be varied between 10 and 60. The adjustment is necessary to equalize the levels of the x and y output channels and to optimize the dynamic range of the compass.

I chose to use a Linear Technology LT1078 dual operational amplifier for this stage. The LT1078 is a micropower device, specified for single supply operation, which has excellent drift and noise characteristics.[2] The dual package also saves space, since only one chip is required for both channels.

3.3.2 3.3 Hz Filter

The primary amplifier is followed by an 8^{th}-order switched-capacitor Bessel filter with a 3.3 Hz corner frequency. This filter removes noise such as spikes and AC fields due to robot motors, and the ever-present 60Hz interference. The filter also helps to reduce the intrinsic noise from the Hall effect sensor itself. Furthermore, the filter limits the response time of the compass, which is actually a useful feature since it smooths out the data when a robot is bumping and jostling along.

This filter is wholly contained on a Maxim MAX292 chip, which requires only one external component, a capacitor to set the corner frequency. The chip comes in two flavors: a Butterworth filter and a Bessel filter. Although a Butterworth filter response has a sharper cut-off, the Bessel response yields a minimum settling time.[Horo., p. 265ff][AN-6] Acting as a critically damped resonator, a Bessel filter will approach a steady-state output as fast as is possible without overshoot or ringing. This is just what the compass needs, since the output shifts between one essentially DC output to another.

Since switched-capacitor filters are discrete-time, sampled systems, the MAX292 is prone to aliasing problems, where frequencies higher than half the sampling rate can be reflected into the filter's passband.[Sieb., pp. 435-439] Inserting a simple RC circuit before the filter input reduces the aliasing effect. The sampling rate of the MAX292 is 330 Hz (100 times the corner frequency); the RC cutoff is set at 16 Hz, providing -27 dB of attenuation at the sampling frequency.

3.3.3 Secondary Amplifier

The last stage of the sensor circuit is another amplifier, which is actually contained within the MAX292. This op-amp is connected in the same configuration as the primary amplifier, although it only provides a fixed gain of 3. This op-amp also can only swing within 1 volt of the supply rails, limiting the dynamic range of the compass to ± 1.5 volts. The offset control in this stage is used to remove any offset introduced by the filter and to fine-tune the total DC offsets of the compass. The op-amp outputs have $1k\Omega$ resistors to provide over-current protection for the 68HC11, in case the output should ever exceed $+5$ volts.

[2] According to the 1990 spec sheet, $0.6\mu V_{p-p}$ noise in a $0.1Hz$ to $10Hz$ bandwidth, and $0.4\mu V/°C$ offset drift.

The complete circuit yields a DC voltage gain ranging from 30 to 180. The compass uses 5 integrated circuits and has a total of six knobs to tweak — two offset adjusts and one gain control for each channel.[3] All of the components are available in surface-mount packages. Also, many of the passive components are identical, simplifying construction.

[3] Calibration will be discussed in Section 5.1.

Chapter 4

The Software

The software portion of the compass package consists of a short 68HC11 subroutine which accepts the two one-byte values resulting from A/D conversion of the compass sensor signals. The routine returns a one-byte result which ranges from 0 to 239, representing a heading in units of 1.5°. This format was chosen because the 68HC11 is an 8-bit machine; the routine is easier to implement if it calculates single-byte results.

4.1 Method of Calculation

The calculation of the heading is pretty simple: divide one component by the other and find the arctangent of the result. An alternate method would be to first compute the magnitude of the Earth's field as projected onto the horizontal plane (by squaring the components, etc.), and then find the arcsine of one component divided by this magnitude. Both methods are equivalent as far as precision is concerned: given an error Δ in the x and y components due to noise, the error in angle for either technique is

$$\Delta\theta = \frac{\Delta}{\sqrt{x^2 + y^2}}$$

in radians, which is just the relative error of the field measurement. From this expression, it is evident that the maximum precision possible with this compass, using the full range of an 8-bit A/D conversion, is $\frac{1}{128}$ radians, or 0.45°.

Finding the arctangent is the preferred method, since it requires less computation than the magnitude/arcsine approach — in particular, no square roots. However, the other method would be necessary to interpret the data from a full three-dimensional compass (as suggested at the end of Chapter 2).

4.2 Implementation

A flowchart of the 68HC11 implementation is shown in Figure 4-1; the annotated assembly code is presented in Appendix C. The heart of this routine is the TangentTable, a 32-byte long look-up table containing the tangents of angles from 0° to 45° in 1.5° intervals. Each value is stored as a one-byte binary-weighted fraction,[1] the same format used by the 68HC11 for the result of its FDIV [fractional divide] instruction.

The routine expects to find the compass sensor values in the a- and b-accumulators of the microprocessor. The routine's first step is to subtract 128 from each input value. The zero-field signal in each compass channel is assumed to be 2.5 volts, which is converted to a value of 128 by the A/D ports on a 68HC11. Subtracting 128 makes this value a two's complement signed integer representing the voltage above or below the zero-field voltage.

After subtracting, the signs of the two new values are recorded and the values are made positive, if they are not already. The fractional divide instruction only works with unsigned numbers, but the signs of both components are needed to determine the correct quadrant to which the heading belongs.

The routine compares the components to decide the order in which to divide them, so that the result is always fractional. This way, the result is the tangent of some angle in the 0° to 45° range, or the cotangent of an angle in the 45° to 90° range. The routine makes a note of which order the division will be performed in, so that it can choose the correct half-quadrant later. The division is then performed, yielding a tangent in two-byte binary fraction form.

Finally, the routine looks up this tangent in the Tangent Table. Only the first byte of the tangent is used. The routine estimates the location in the table by dividing this byte by 8, and then begins searching forward through the table. When the value in the table exceeds the tangent byte the search is finished, and the position in the table gives the angle.

To finish up, the routine performs the necessary subtractions to move the angle into the correct quadrant. The final result is returned in the b-accumulator.

This routine, including instructions and the look-up table, is 82 bytes long and requires one RAM location for flag storage. At most, the routine requires 237 machine cycles to convert a pair of compass values into a heading. Given a standard 2 MHz clock, this amounts to under $119\mu s$ per reading.

[1] The most significant bit represents $\frac{1}{2}$, the next $\frac{1}{4}$, etc., as if a binary point were just to the left of the MSB.

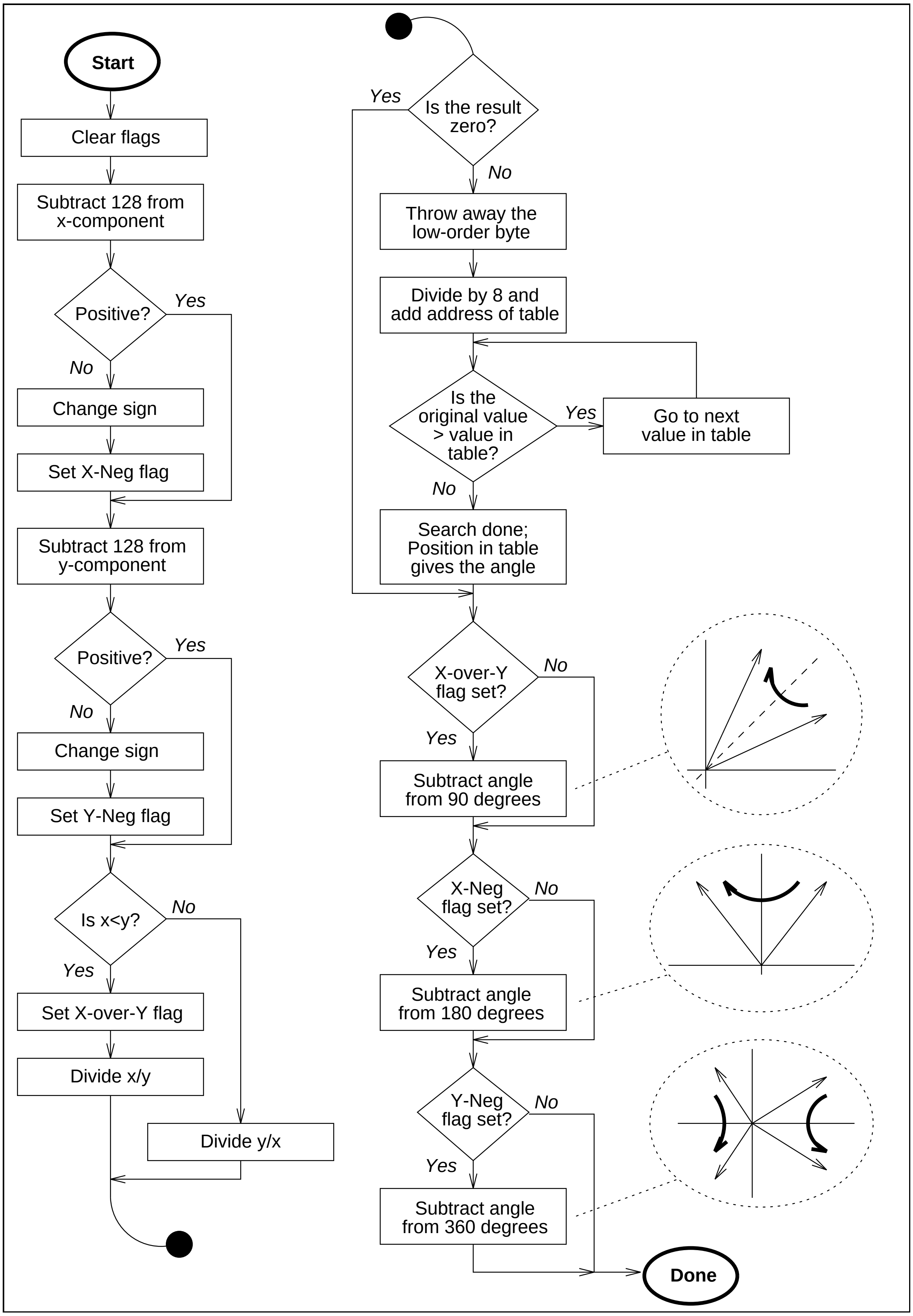

Figure 4-1: Flowchart of the 68HC11 routine used to compute compass headings

4.3 Propagation of Error

For calibration purposes, it is helpful to know how gain and offset errors in the sensor affect the calculated heading. Suppose the measured signals are $(\alpha x + \delta_x)$ and $(\beta y + \delta_y)$, where x and y are the true signals; ideally $\alpha = \beta = 1$ and $\delta_x = \delta y = 0$. Assuming that $|y| < |x|$, the measured angle is

$$\theta_{meas} = \arctan\left(\frac{\beta y + \delta_y}{\alpha x + \delta_x}\right).$$

A first-order expansion in the error factors yields

$$\theta_{meas} \approx \arctan\left(\frac{y}{x}\right) + \left(\frac{xy}{x^2 + y^2}\right)\left[(\alpha - \beta) + \frac{\delta_y}{y} - \frac{\delta_x}{x}\right].$$

In this expression, $\arctan(\frac{y}{x})$ is the true angle, $(\alpha - \beta)$ is the gain imbalance between the two channels, and $\frac{\delta_y}{y}$, $\frac{\delta_x}{x}$ are the relative offset errors in the two channels.

This expression can be approximated at two extremes. First, if $0 \approx |y| << |x|$,

$$\theta_{meas} \approx \theta_{true} + \left(\frac{y}{x}\right)\left[(\alpha - \beta) + \frac{\delta_y}{y}\right].$$

Since y is small, δ_y becomes critical in determining the measured heading.

At the other extreme, if $|y| \approx |x|$,[2]

$$\theta_{meas} = \theta_{true} \pm \frac{1}{2}\left[(\alpha - \beta) + \frac{\delta_y - \delta_x}{x}\right].$$

The measured heading will depend primarily on the gain imbalance if the x and y channel offsets are relatively small.

Altogether, these expressions reveal that:

1. in the cardinal directions (N, S, E, W) the channel offsets will determine the accuracy of the compass, and

2. along the 45° lines (NE, NW, SE, SW) the gain imbalance between channels will probably be the determining factor.

These two facts are useful in the calibration process, discussed in Section 5.1.

[2] If $|y| > |x|$ then the fraction is inverted before the calculation; recall that the software always evaluates a fractional arctangent.

Chapter 5

The Prototype

The prototype of the compass was built using PC-mount components on a breadboard, instead of using surface mount components, with the understanding that a test batch of printed circuit boards would be produced later. All of the calibration and testing outlined in this chapter was performed in "The Corral," the area on the 9^{th}-floor of the MIT Artificial Intelligence Lab where the R1's are used.

5.1 Calibration Procedure

Before the compass will work properly, it must be calibrated. The calibration consists of:

1. equalizing the sensitivity of the two channels, and
2. nulling out DC offsets in the circuitry, so that the zero-field output is 2.5 volts.[1]

The calibration procedure uses an oscilliscope and a mechanical compass[2], and must be performed someplace where the ambient magnetic field is not distorted by nearby ferrous objects.

The first step is to find a signal in both channels. Both amplifier gains are decreased to their minima, and the fine offset adjusts are centered. The coarse offset of each channel is adjusted until the output is near 2.5 volts and no longer saturates the output stage.

Next, the gain is adjusted so that the peak-to-peak output of each channel is 2.7 volts, 90% of the peak maximum output swing of the amplifier. The peak-to-peak output is measured one channel at a time by turning the compass until the output is at a maximum, and then reversing the orientation to find the minimum. The offset controls need to be adjusted so that the output is relatively well centered about 2.5 volts, otherwise the outputs will be clipped.

[1] This assumes that the high and low reference voltages for the A/D converter on the 68HC11 are 5 and 0 volts, respectively. In any case, the zero-field output of the compass should always be at the center of the ADC range — a zero-signal should be converted to a value of 128.

[2] that is, the kind with a needle.

Finally, the DC offsets need to be properly set. This is crucial because, as explained in Section 4.3, it is primarily the output of a channel near the reference voltage that determines the heading. For this step, a mechanical compass is used to orient the electronic compass to magnetic north, and the offset of the x-component channel is adjusted to set the output to exactly 2.5 volts. The compass is then rotated by 90° and the same adjustment is made to the y-component channel. Once the offsets are set correctly, one of the output channels will read 2.5 volts in each of the cardinal directions (north, south, east, and west).

An alternate method for performing this last step is to use a robot instead of an oscilliscope. Rather than adjusting the offset controls to yield a 2.5 volt output, they can be adjusted so that the robot reports the correct headings — 0, 120, 60, and 180 — in the cardinal directions. Then, the compass can be oriented along the 45° lines and the gain of one of the channels can be tweaked to further improve the accuracy. The best calibration method is a combination of coarse adjustment with an oscilliscope, followed by fine-tuning with a robot for verification.[3]

The compass is now ready for operation. It should not have to be recalibrated again, unless it is moved to a considerably different latitude. As the latitude changes, the inclination of the Earth's field into the ground changes, and the magnitude of the field projected onto the horizontal plane may increase enough to saturate the compass output. The solution to this is to recalibrate the compass with a reduction of amplifier gain.

5.2 Prototype Performance

I tested the performance of the prototype compass by sampling headings at 24 rotational positions (15° intervals) starting from magnetic north (as determined by a mechanical compass). At each position, I recorded 10 heading values, reported once per second. The compass processing was performed by Bran, one of the R1 robots.

The results are shown in Figure 5-1. This graph depicts the normalized measured heading compared to the true heading:

$$(\rho, \theta) = (1 + \frac{\theta_{compass} - \theta_{true}}{120}, \theta_{true})$$

where $\theta_{compass}$ and θ_{true} are measured in units of 1.5°.[4] Ideally, the plot should be a unit circle, indicating that there is no compass error. A circle of larger or smaller radius indicates a constant angular offset. The significance of this plot lies in the fluctuation of the radius, which shows the non-linearities in the compass response.

The total systematic error of the compass, as shown in the graph, is under 10%. The random

[3] What matters anyhow is what the robot thinks, not what the oscilliscope thinks.
[4] 120 compass units = 180°

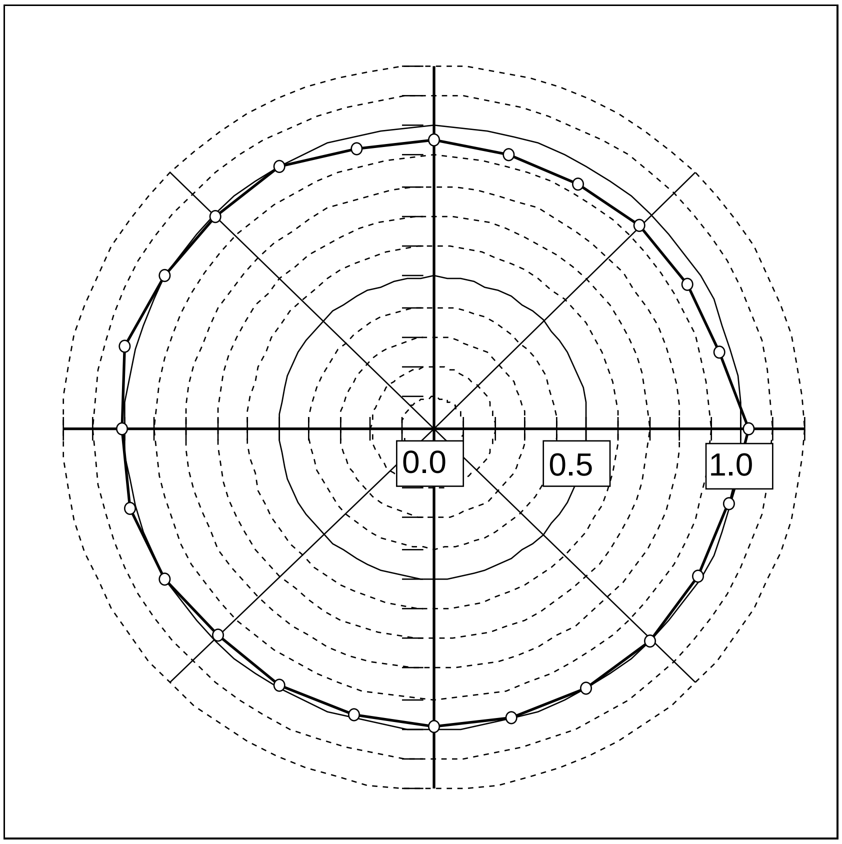

Figure 5-1: Graph of normalized measured heading vs. true heading.

error, induced by sensor noise, is $\pm 1.7°$. This was determined from the standard deviation in the sets of heading data recorded at each position.

I also measured the other specifications of the prototype. With the 5 volt supply, it draws 70 mA of current, or 350 mW of power.[5] The size of the sensor head is $1\frac{1}{8}'' \times 1\frac{1}{8}'' \times \frac{1}{2}''$, and the estimated height of a surface-mount circuit board is $\frac{1}{2}''$. The sensor head weighs 2 ounces, and the surface-mount circuit board should weigh less than 1 ounce. The cost of the components, if bought in small quantities, totals \$45. A comparison of the prototype specifications and the original design goals is shown in Table 5.1.

	Prototype	Design Goal
Size	$1\frac{1}{8}'' \times 1\frac{1}{8}'' \times 1''$ (est.)	$1''$ cube
Weight	3 ounces (est.)	$\leq$ 3 ounces
Power	+5v at 70mA	+5v at 25mA
Output	1–4v range	0–5v range
Precision	$\pm 1.7°$	$\leq \pm 5°$
Accuracy	$\pm 6°$	$\leq \pm 5°$
Cost	$\sim$ \$45	$\leq$ \$50

Table 5.1: Comparison of prototype specifications versus original design goals.

[5] Nearly a third of this power is wasted by the voltage converter chip.

Chapter 6

Conclusion

My intention for this project was to design a simple electronic compass, with an emphasis on size and ease-of-use rather than accuracy. I am happy to say that I have met essentially all of my design goals. I have created a general-purpose electronic compass sensor that can be easily added to any robot which has available analog-to-digital conversion ports. I have also written a software driver for use with the Motorola 68HC11, a microprocessor commonly used on small robots, particularly those at the MIT Mobile Robotics Lab.

The next step for this project is to transfer the circuitry to a printed circuit board. All of the components used in the compass are available in surface-mount packages, so that the PC board will be as small as the sensor mount. The final manifestation of the compass will be a compact block with four leads: two for power, and two for signals. Some additional reworking of the sensor head may be necessary to make to the device easier to produce in large (> 1) quantities.

Finally, the robots in the Mobot Lab will have a simple sense of orientation. And hopefully, someday my fish will, too.

Appendix A

Compass Electronics Schematics

The following are the schematic diagrams for the compass electronics. The part numbers refer to the component list in Appendix B.

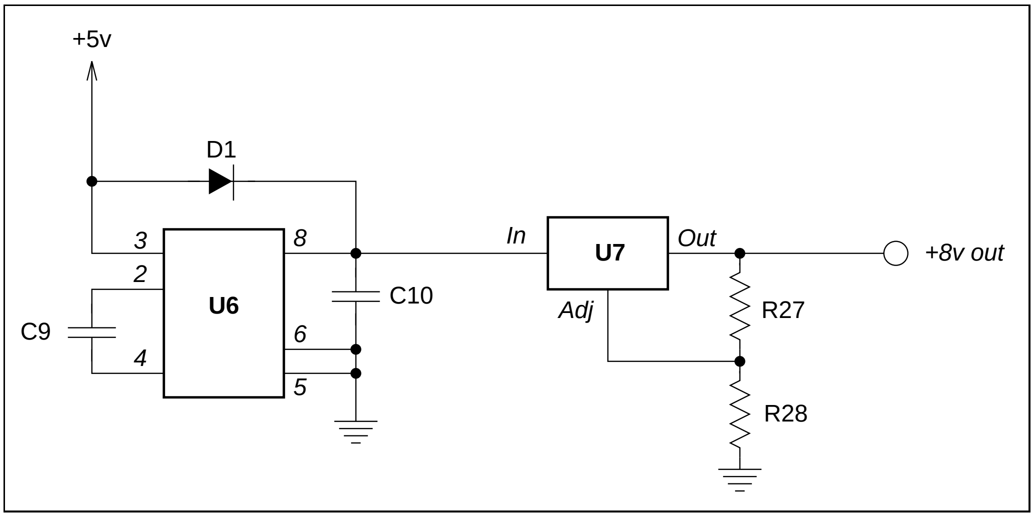

Figure A-1: 8 volt power supply circuit.

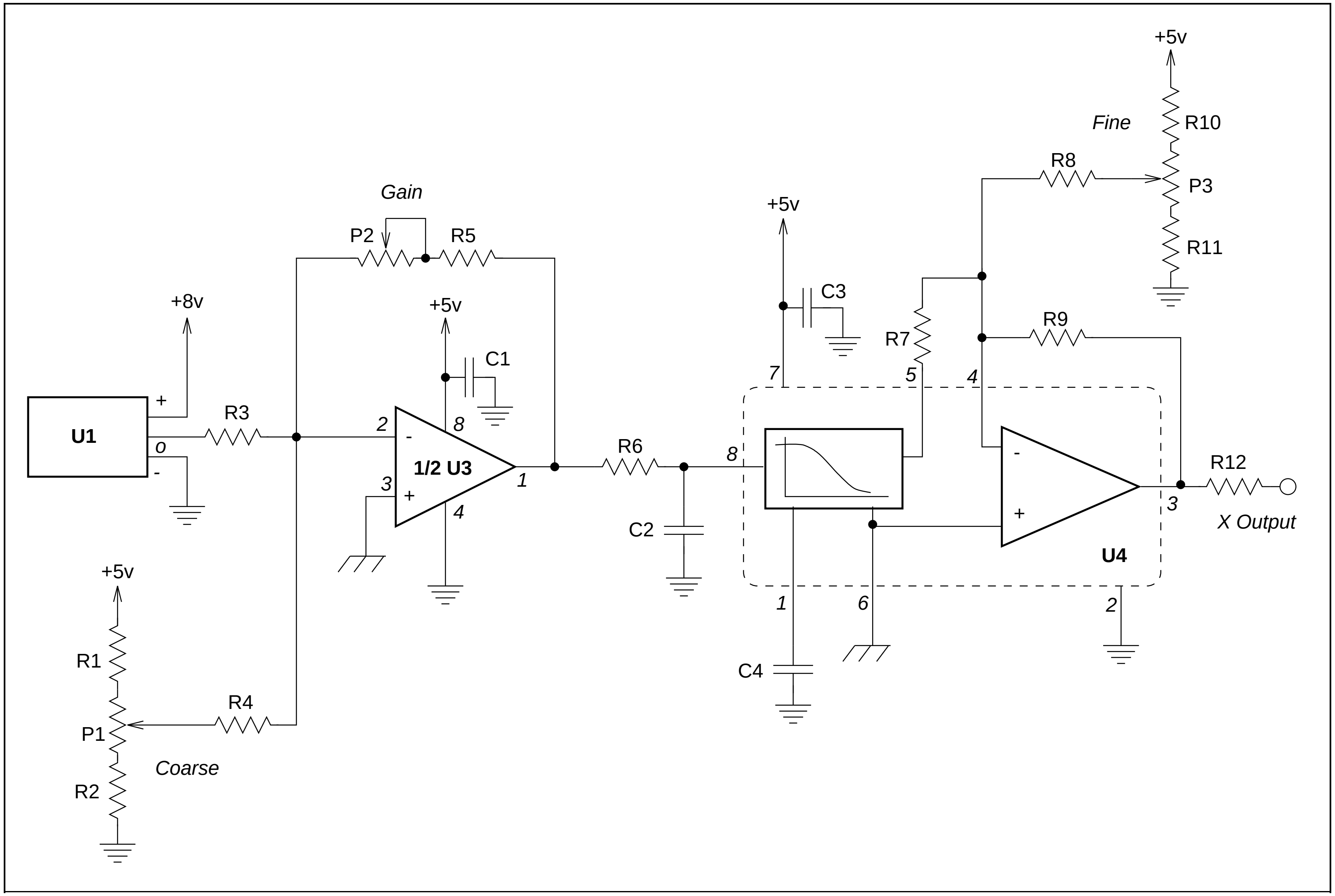

Figure A-2: X-component channel, sensor and amplifiers.

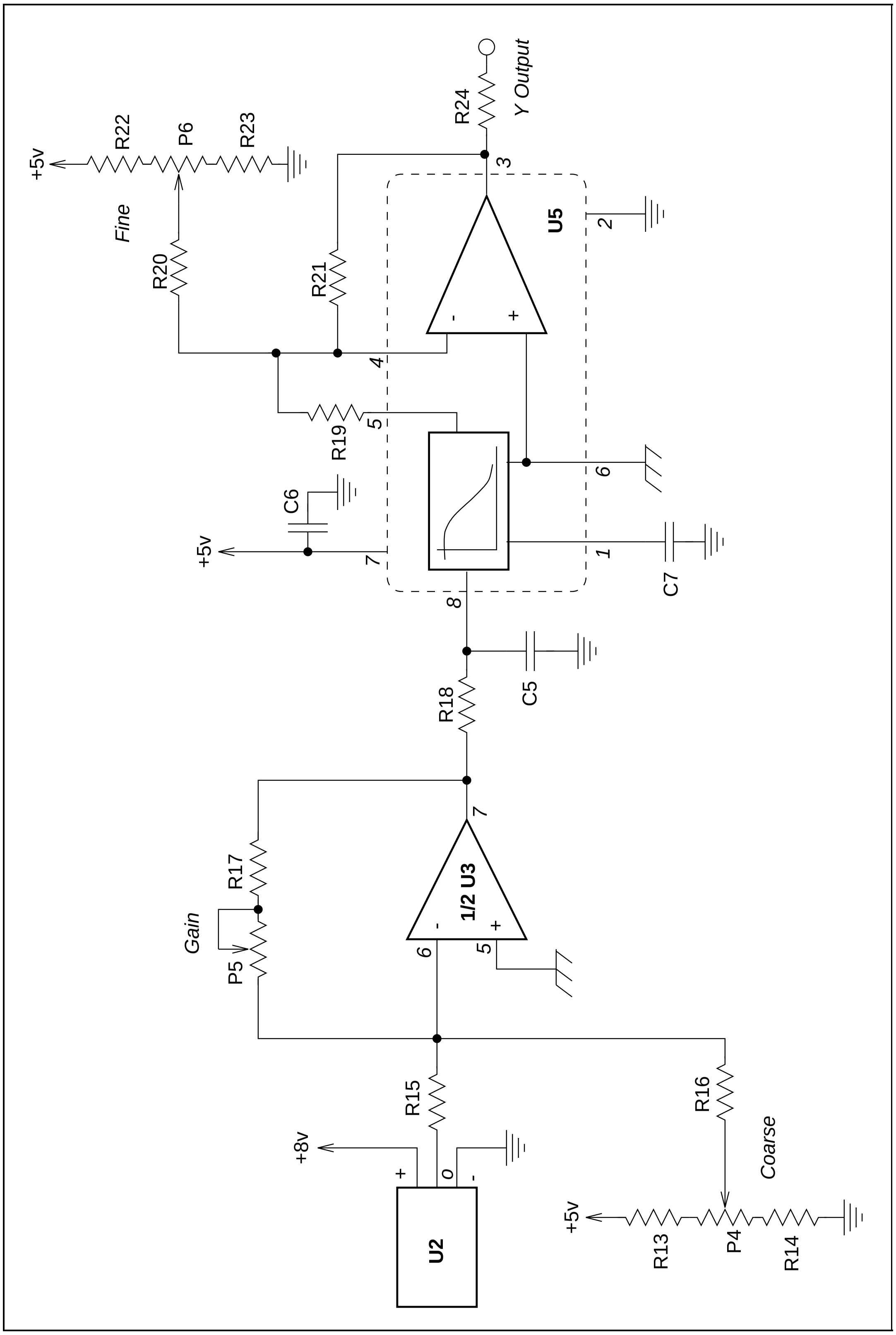

Figure A-3: Y-component channel, sensor and amplifiers.

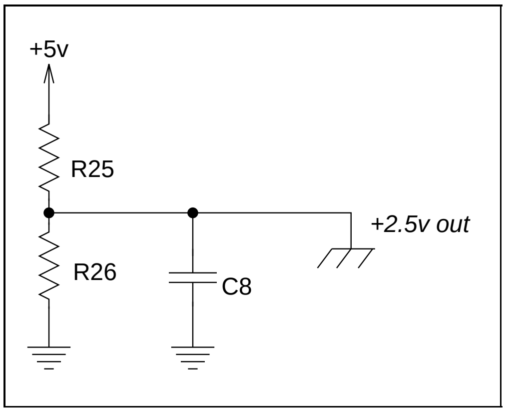

Figure A-4: 2.5 volt “ground” reference.

Appendix B

Component List for the Compass

Schematic #	Type	Description	Manufacturer
U1, U2	SS94A1F	Hall Effect Sensor	Honeywell/Microswitch
U3	LT1078	Dual Micropower Op-Amp	Linear Technology
U4, U5	MAX292	8^{th}-Order Low-Pass Bessel Filter	Maxim Integrated Products
U6	MAX660	CMOS Voltage Converter	Maxim Integrated Products
U7	LM317	Adj. Positive Voltage Regulator	National Semiconductor
D1	1N5817	Schottky Barrier Diode	
C1, C2, C3, C4, C5, C6, C7, C8	$0.1\mu F$	Ceramic Capacitor	
C9, C10	$47\mu F$	Electrolytic Capacitor	
R1, R13	$5.49k\Omega$	1% Precision Metal Film Resistor	
R2, R12, R14, R24	$1.00k\Omega$	1% Precision Metal Film Resistor	
R3, R4, R7, R8, R15, R16, R19, R20, R25, R26	$10.0k\Omega$	1% Precision Metal Film Resistor	
R10, R11, R22, R23	$1.50k\Omega$	1% Precision Metal Film Resistor	
R5, R6, R17, R18	$100k\Omega$	1% Precision Metal Film Resistor	
R9, R21	$30.1k\Omega$	1% Precision Metal Film Resistor	
R27	$221k\Omega$	1% Precision Metal Film Resistor	
R28	$1.21k\Omega$	1% Precision Metal Film Resistor	
P1, P3, P4, P6	$1k\Omega$	12-Turn Potentiometer	
P2, P5	$1k\Omega$	12-Turn Potentiometer	

(“Schematic #” refers to schematics in Appendix A.)

Appendix C

Listing of Compass Software

This is the compass heading calculating routine, written in assembly language for the Motorola 68HC11 microprocessor.

```
;ADDR--DATA-------------MNEMONIC----------------------------------
                    ;;; Constant definitions...
                    ;;;  Location of flag register:
                DE        (=V COMPASSFLAGS 222)
                    ;;;  The flag bits:
                 8        (=C X-OVER-Y-BIT 8)
                 4        (=C X-NEG-BIT 4)
                 2        (=C Y-NEG-BIT 2)

                    ;;; Compass Processing Routine
                    ;;;   --expects x-component in accum-a,
                    ;;;             y-component in accum-b
                    ;;;   --result (heading in 1.5 degree intervals)
                    ;;;       is returned in accum-b
              86C4  COMPASS-CALC
                    ;;; Suspend interrupts and save x-register;
                    ;;;  interrupt routines tend to expect
                    ;;;  RegisterBase in x-reg
86C4  0F                  (SEI)
86C5  3C                  (PSHX)
                    ;;; Clear flags and put location
                    ;;;  in y-reg for indexed access later
86C6  7F 00 DE            (CLR COMPASSFLAGS)
86C9  18 CE 00 DE         (LDY ! COMPASSFLAGS)
                    ;;; Subtract offset from x-component,
                    ;;;  set a flag if result is negative,
                    ;;;  and take absolute value
86CD  80 80               (SUBA ! 128)
86CF  2A 05               (BPL CC-X-IS-OK)
86D1  40                  (NEGA)
86D2  18 1C 00 04         (BSET &Y 0 X-NEG-BIT)
                    ;;; Do same for y-component
```

```
             86D6  CC-X-IS-OK
86D6  C0 80              (SUBB ! 128)
86D8  2A 05              (BPL CC-Y-IS-OK)
86DA  50                 (NEGB)
86DB  18 1C 00 02        (BSET &Y 0 Y-NEG-BIT)
                   ;;; Compare x to y to see order of division,
                   ;;;  i.e. x/y or y/x.  Set flag, and set up
                   ;;;  registers for division
             86DF  CC-Y-IS-OK
86DF  11                 (CBA)
86E0  22 07              (BHI CC-Y-OVER-X)
             86E2  CC-X-OVER-Y
86E2  18 1C 00 08        (BSET &Y 0 X-OVER-Y-BIT)
86E6  36                 (PSHA)
86E7  20 02              (BRA CC-DO-DIVIDE)
             86E9  CC-Y-OVER-X
86E9  37                 (PSHB)
86EA  16                 (TAB)
                   ;;; Divide, using fractional division,
                   ;;;  and put result in accumulator
             86EB  CC-DO-DIVIDE
86EB  4F                 (CLRA)
86EC  8F                 (XGDX)
86ED  33                 (PULB)
86EE  4F                 (CLRA)
86EF  03                 (FDIV)
86F0  8F                 (XGDX)
                   ;;; Zero?  Then we're done.
86F1  27 13              (BEQ CC-LOOK-UP-DONE)
                   ;;; Use only high byte of result; divide
                   ;;;  by 8 to get place to start searching
                   ;;;  in table
86F3  16                 (TAB)
86F4  54                 (LSRB)
86F5  54                 (LSRB)
86F6  54                 (LSRB)
86F7  CE 87 26           (LDX ! TANGENTTABLE)
86FA  3A                 (ABX)
86FB  09                 (DEX)
                   ;;; Look through table of tangents; the
                   ;;;  address we stop at yields the arctan
             86FC  CC-KEEP-LOOKING
86FC  08                 (INX)
86FD  A1 00              (CMPA &X 0)
86FF  22 FB              (BHI CC-KEEP-LOOKING)
8701  09                 (DEX)
8702  8F                 (XGDX)
8703  83 87 26           (SUBD ! TANGENTTABLE)
                   ;;; If x/y, we want arccot, so subtract
                   ;;;  from 90 degrees
             8706  CC-LOOK-UP-DONE
8706  18 1F 00 08 04     (BRCLR &Y 0 X-OVER-Y-BIT CC-45DEG-OK)
870B  86 3C              (LDAA ! 60)
870D  10                 (SBA)
```

```
870E  16                  (TAB)
                    ;;; If x was negative, adjust quadrant;
                    ;;;  subtract from 180 degrees
              870F  CC-45DEG-OK
870F  18 1F 00 04 04      (BRCLR &Y 0 X-NEG-BIT CC-X-FLIP-DONE)
8714  86 78               (LDAA ! 120)
8716  10                  (SBA)
8717  16                  (TAB)
                    ;;; If angle is zero, we're done.
                    ;;; If y was negative, adjust quadrant;
                    ;;;  subtract from 360 degrees
              8718  CC-X-FLIP-DONE
8718  27 09               (BEQ CC-Y-FLIP-DONE)
871A  18 1F 00 02 04      (BRCLR &Y 0 Y-NEG-BIT CC-Y-FLIP-DONE)
871F  86 F0               (LDAA ! 240)
8721  10                  (SBA)
8722  16                  (TAB)
                    ;;; Finished!
                    ;;; Restore x-register, turn on interrupts
                    ;;;  and return to user
              8723  CC-Y-FLIP-DONE
8723  38                  (PULX)
8724  0E                  (CLI)
8725  39                  (RTS)
                    ;;; Table of Tangents
                    ;;; Each byte corresponds to the high-byte
                    ;;;  of the binary-weighted fraction of
                    ;;;       TAN(theta + 0.75 degrees)
                    ;;;  where theta begins at 0 and increases
                    ;;;  in 1.5 degree increments
                    ;;; The first byte in the table is a zero
                    ;;;  needed for the search algorithm
                    ;;; The last byte in the table is an FF
                    ;;;  which stands for TAN(45 degrees)
              8726  TANGENTTABLE
8726  00 03               (!16 3)
8728  0A 11               (!16 2577)
872A  18 1E               (!16 6174)
872C  25 2C               (!16 9516)
872E  33 3A               (!16 13114)
8730  41 48               (!16 16712)
8732  4F 57               (!16 20311)
8734  5E 66               (!16 24166)
8736  6E 76               (!16 28278)
8738  7E 87               (!16 32391)
873A  8F 98               (!16 36760)
873C  A2 AB               (!16 41643)
873E  B5 BF               (!16 46527)
8740  CA D5               (!16 51925)
8742  E1 ED               (!16 57837)
8744  FA FF               (!16 64255)
```

Bibliography

[AN-6] *AN-6: Choose the Right Lowpass Filter*, application note; Maxim Integrated Products, Inc., Sunnyvale, CA, 1991.

[Bell] *Hall Generator Handbook,* F.W. Bell Corporation, Orlando, Florida, 1992.

[Bolt.] Bolton, Clive. *A Digital Compass*, Undergraduate Thesis; Massachusetts Institute of Technology, Dept. of EECS; May, 1984.

[Grif.] Griffiths, David J. *Introduction to Electrodynamics,* 1989: Prentice-Hall, New Jersey.

[Horo.] Horowitz, Paul, and Hill, Winfield. *The Art of Electronics*, 1989: Cambridge University Press, Cambridge.

[Sieb.] Seibert, William. *Circuits, Signals, and Systems*, 1986: MIT Press, Cambridge, MA.