TRIPOD FLOATER:
AN “ACTIVE MAGNETIC BEARING” - DEMONSTRATOR

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INTRODUCTION

The Tripod Floater, topic of this paper, is an Active Magnetic Bearing (AMB) Demonstrator.

Goal

Goal of building this Tripod Floater is to demonstrate and increase technical capabilities and knowledge (see [4]).

Making this module completely cable-less or wireless (which is the main topic of this paper) is fueled by the same desire, more so than pursuing a specific product or application.

Active Magnetic Bearing Benefits

Some of the benefits of AMBs over traditional bearings are the ability of active vertical movements, vacuum compatibility and the fact that performance mainly depends on measurement system quality as opposed to bearing surface quality. Besides that, AMB-‘smarts’ reside in software, allowing for features like diagnostics and self-tuning capabilities.

Motivation for design choice

The specific choice for this Tripod Floater's architecture (a module with three vertical AMBs hanging from a metal plate) aims to investigate and demonstrate the (im)-possibilities of simplifying Active Magnetic Bearing designs. Most often, especially in the way AMBs have been applied in semiconductor stages over the past few years, controls architectures have been elaborate and expensive. Working towards a modular design aims to:

- Reduce price;
- Simplify design;
- Make AMB technology accessible to more engineers and a wider range of applications.

As mentioned, making the module cable-less is the main topic of this article. This required:

- An alternative controller implementation and power source;
- Implementing a wireless communication protocol;
- The use of PWM drivers instead of linear amplifiers.

Contents

This paper focuses on 4 Tripod Floater changes for making it completely cable-less. The Floater’s architecture is discussed in the first section. After that, 4 changes (controller, amplifier, power source and wireless communication) will be discussed, and the section after that discusses a few ‘lessons learned’ while working on the tripod floater.

In the final section some performance results will be illuminated.

TRIPOD FLAOATER ARCHITECTURE

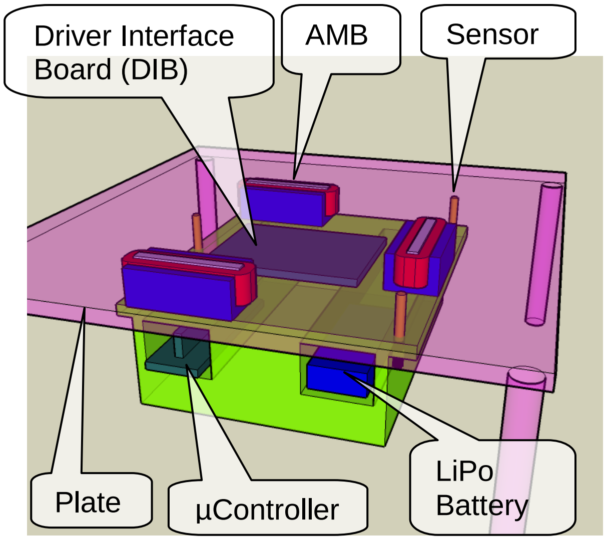

FIGURE 1. Model of cable-less Tripod Floater.

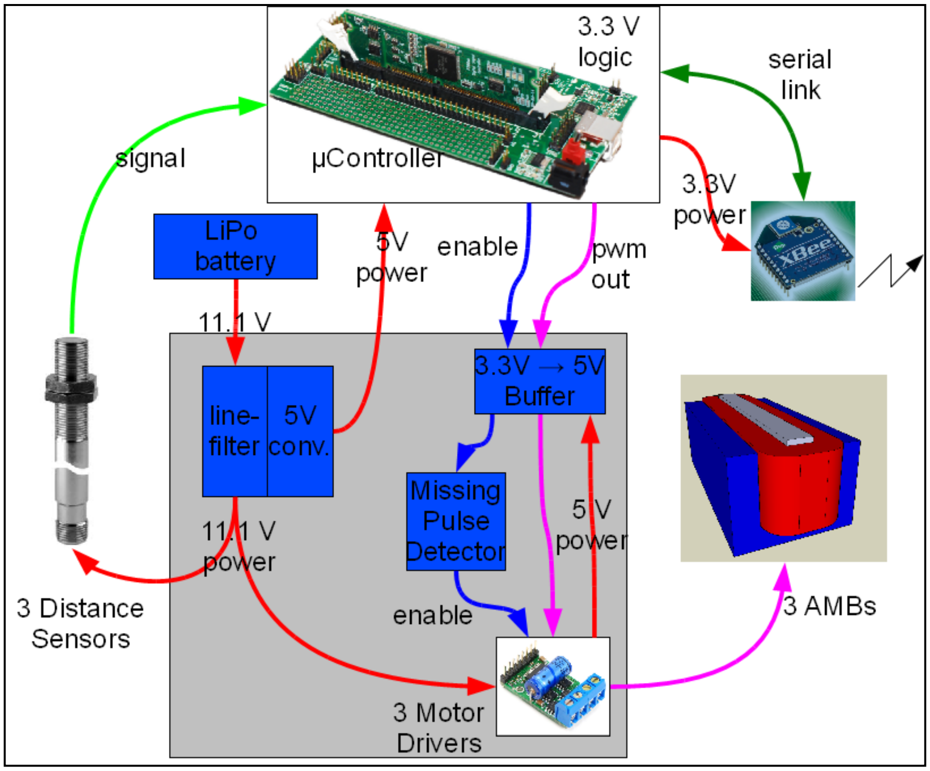

FIGURE 2. Schematics of Tripod Floater architecture.

Tripod Floater Architecture

The basic architecture of the Tripod Floater consists of an approximately 7 kg module hanging from a metal plate (see *FIGURE 1*) by means of 3 Electro Magnets (coils with permanent magnets, a.k.a. Active Magnetic Bearings). The distance between module and plate is measured using 3 sensors, and a sensor transformation calculates three individual gaps between the Active Magnetic Bearings (AMBs) and plate.

3 PID controllers (implemented in a µController) regulate the AMB currents, maintaining a fixed distance between module and plate. The result is a constant gap between the AMBs and plate of typically 0.5 mm (for high performance applications) to 2 mm (for the Tripod Floater).

For the Tripod Floater version as described in this article, controller and battery were placed in two slots in the module's housing, and a *Driver and Interface Board* (DIB) was placed in between AMBs and sensors, as depicted in *FIGURE 1* and *FIGURE 6*. The DIB (see also *FIGURE 2*) implements:

- Power filtering;
- 11.1 V → 5 V conversion;
- Sensor interfacing (power to sensors and signal to µController);
- AMB driver interface;
- Additional safety and control logic.

Control Objectives

It is important to realize that the AMB-gap is actively controlled, resulting in different control objectives:

1. *Constant gap*, resulting in a friction-less multi-dimensional bearing;
2. *Vertical Reference following*, e.g. tooltip or microscope lens.
3. *Constant Current*, to minimize power consumption. In this case, the gap between the AMBs and plate would adapt to a changing load. For example, an increasing load would require an increase of magnetic force which is achievable with a decreased magnetic gap, resulting in equilibrium between load and the sum of three magnetic forces.

Bill Of Materials

In an attempt to make AMB technology more accessible an attempt was made to show it is possible to keep costs low. The sensors and AMBs themselves account for the majority of the demonstrator's costs. Electronics and mechanical components are available from www.digikey.com, www.Mouser.com and hobby stores as experimenter kits a total of about $700.

TABLE 1. Condensed Tripod Floater BOM.

3 distance sensors	$ 1200
3 AMBs [i]	$ 1500
Cables	$ 50
Motor Drivers	$ 150
Misc. electronics components	$ 50
2 Batteries / Charger	$ 85
TI µController Experimenters Kit	$ 99
Zigbee Development Kit	$ 200
Total:	$ 3334

IMPLEMENTATION CHANGES

This section describes four major implementation changes with respect to an earlier Tripod Floater version. These changes are:

1. Move controller from external dSpace to onboard microprocessor;
2. Replace linear amplifiers with on-board PWM amplifiers;
3. Replace external power-supply with LiPo battery;
4. Replace existing Matlab-dSpace interface (for animation and tuning purposes) with wire-less Zigbee communication.

On Board Controller

For an earlier Tripod Floater version, dSpace was used to implement sensor transformations and PID controllers, allowing for faster experiments while focusing on integration.

For the current version, a Texas Instruments (www.TI.com) floating point µController (TMS320F28335, see [3]) was used. A short investigation into specification in combination with experience from other projects made this an optimal choice.

A library with PIDs and 1st and 2nd order filters was built, and implemented using the following characteristics:

- 100 MHz CPU clock cycle;
- 3 PID-loops at 10 kHz;
- 12 bit ADC;
- 18 bits, 15 kHz PWM [ii].

An Experimenter Kit docking station with separate controlCARD allows for fast and easy experimentations (see [3] and *FIGURE 3*).

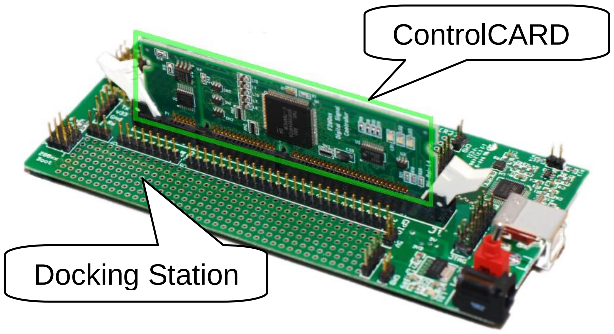

FIGURE 3. TI Experimenter Kit Docking-Station and controlCARD.

PWM Motor Drivers

To replace external linear amplifiers, three PWM motor drivers from robotics hobby parts supplier Pololu (www.pololu.com) were used.

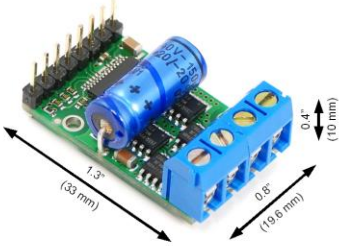

FIGURE 4. Pololu 18v15 Motor Driver.

These three drivers were ideal in size and rating to drive AMBs and easy to integrate onto the "Driver and Interface Board" (DIB) on top of the module in between all AMBs (see *FIGURE 6*).

Typical driver characteristics (also see [1]) are:

- 5.5 – 30 V range input voltage;
- Up to 40 kHz PWM driving frequency;
- 15 A continuous drive current (no heat sink);
- 33 x 19.6 x 10 mm.

For the controls-objective as used for this application (constant/low current), heat generation in the drivers is minimal.

LiPo Battery

A 3 cell Lithium-Polymer (LiPo) battery as often used by model-plane and -car hobbyists was use to provide power (see [2]).

Typical battery characteristics are:

- 11.1 V supply voltage;
- 2.2 Ah capacity;
- 44 A max discharge rating.

FIGURE 5. '20C' 11.1Volt Lithium Polymer battery, as often used by model airplane hobbyists.

The total power consumption of the floater is approximately 1.5 [A], most of which is used by the microcontroller and its docking station. This battery allows for up to 5 hours of experimenting time, obviously depending on the type of work.

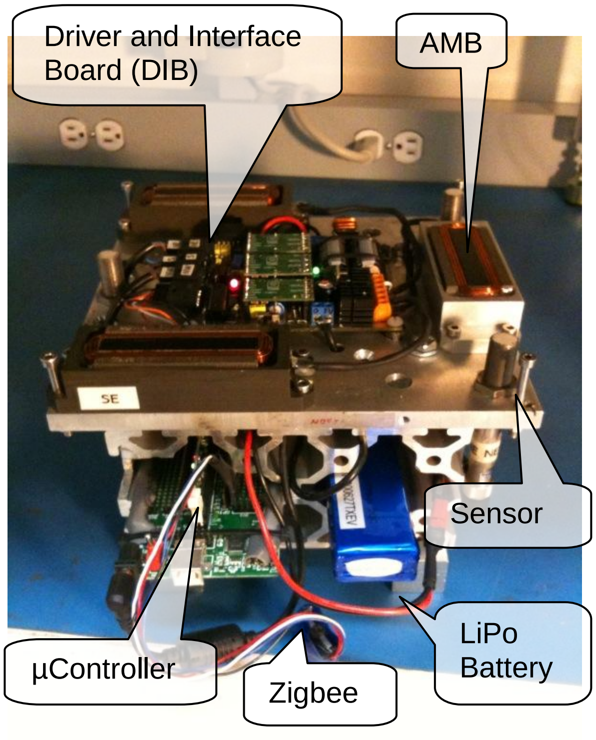

FIGURE 6. Photo of Tripod Floater standing on table.

Zigbee

To implement a means for bi-directional communication between Tripod Floater and Matlab, a Zigbee (www.digi.com) module was used (see *FIGURE 7*). Connected to the micro-controllers build-in serial port peripheral this provides a simple but effective communication port. The Matlab side interface is implemented using a standard Matlab COM interface.

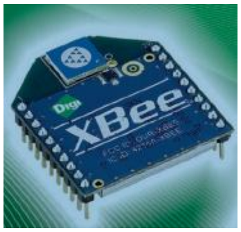

FIGURE 7. Digi's Zigbee module.

At both sides (Matlab and microcontroller), processes continuously monitor serial port buffers for incoming data and send requests for data. This way, a baud rate of 115 kbps was achieved resulting in an animation update frequency of approximately 30 Hz.

LESSONS LEARNED

This section describes several issues that had to be addressed in order to make the Floater work:

1. AMB protection;
2. Amplifier protection;
3. Zigbee power consumption.

AMB Protection

The most basic interface between the micro-controller and the Pololu motor drivers consists of two signals:

- PWM: select PWM mode / off mode
- DIR: determines in which direction the amplifier's H-bridge are switched.

Problem

During normal operation, PWM would be ON, and DIR switches at 15 kHz, resulting in a specific desired current.

During debug sessions however, interrupting µController's operation (e.g. for re-programming) might leave its outputs in a PWM-on state, and DIR in either high or low, resulting in a continuous maximum current through the AMBs. With an approximately 1 Ω resistance, this might not damage the drivers, but could overheat and damage the AMBs.

Solution

To prevent drivers from inadvertently being switched ON, an analogue 'Missing-Pulse-Detector' was implemented and connected to the µController's PWM signal, which was made to pulse at a 10 Hz rate. The 'Missing-Pulse-Detector'-s function is to switch the driver's PWM input OFF when no state-change was observed for longer than 150 ms from mentioned µController's output.

Amplifier Protection

Problem

During module power-up, in some cases the Motor-Driver's DIR input was set high or low before the driver was properly supplied with 5 V to power its internal logic. This would result in an unknown H-bridge state, in one case thought to have damaging the Motor-Driver beyond repairs.

Investigation

Before describing the solution to prevent this failure, it is good to know that:

- A Buffer/Driver IC is used to convert 3.3V µController logic into 5V logic for the driver;
- The Motor-Drivers have a 5V output, capable of driving a few mA;

Solution

In order to prevent the Buffer/Driver to put Motor-Driver's DIR input in an undesired state a change is made in the way the Buffer/Driver is powered: Instead of powering the Buffer/Driver ICs with 5 Volts originating from the power supply, it is now powered using the Motor Driver's 5 Volt output. This way, the Motor-Driver's DIR input will not be set before the Motor-Driver is ready to receive DIR inputs.

Zigbee power consumption

Problem

During wireless communication experiments with Digi's Zigbee module, an audible hissing sound (originating from the AMB actuators) was observed each time a data-set was requested and received. Although no voltage drop was observed in µProcessor- or Motor-Driver-power supply, it was determined that the Zigbee module was temporarily drawing too much current, probably causing a temporary disturbance in controller output.

Investigation

Digi's XBee-PRO Zigbee module, powered using 3.3 Volts from the TI Docking Station, is rated to use 250 mA during data transmission.

Solution

The PRO X-Bee module was replaced with a low-power module, rated at 45 mA during transmission (see [6]).

Remaining challenges

Besides these and other issues that were fixed, several unresolved issues still require attention. As will be mentioned later, a limit-cycling effect occurs when some of the motor drivers are operated around their 0 [A] setpoint. Also, attempts to perform a proper frequency measurement have not been successful yet, for unknown reasons.

PERFORMANCE

This section describes two performance measurements.

- Stand still performance;
- Constant-Current control.

Stand still performance

As a performance indication of this modular AMB demonstrator, *FIGURE 8* shows a 10 µm 'standstill' position error, sampled at 21 Hz using the Zigbee wireless interface.

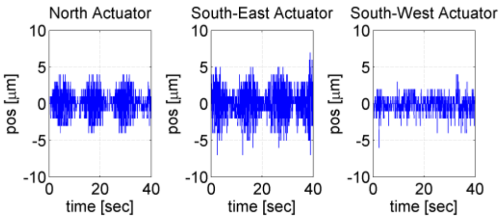

FIGURE 8. Position error during standstill. A noise level of less than 3 μm_{RMS} is observed.

N and SE actuator 'Beating' is caused by aliasing of a higher frequent (yet to be understood) disturbance.

Constant-Current control

As mentioned earlier, one of the control objectives for an AMB module could be to carry additional pay-load at no additional current. Because of its magnetic properties, the attracting force will increase quadratically with decreasing gap.

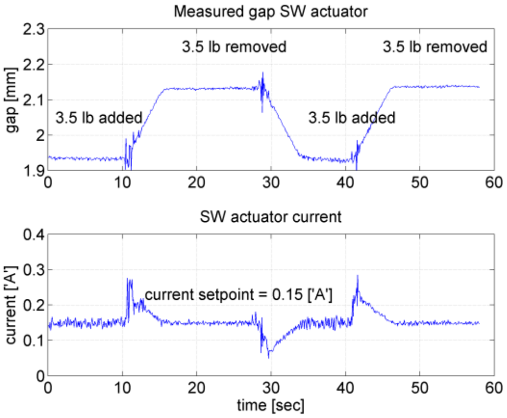

FIGURE 9. When adding and removing an additional payload a 'current controller' changes the gap (see UPPER plot) in order to maintain a current of 0.15 'Amp' (see LOWER plot).

During this experiment (see *FIGURE 9*), a mass of close to 2 kg was added and removed from the 7 kg AMB demonstrator module while floating. A current setpoint of 0.15 'Amp' [iii] was chosen, to avoid the earlier mentioned limit-cycle behavior around a zero current setpoint.

After removing 2 kg of mass (at t = 10 sec), the 'current controller' changes the gap setpoint from 2.13 mm to 1.93 mm in order to maintain a 0.15 'A' current. The 'current controller' simply changes the gap-setpoint with a fixed value each sample when the current is too large or too small.

CONCLUSION

In this paper, some of the work performed on the Tripod Floater, an Active Magnetic Bearing Demonstrator has been described.

Several goals were kept in mind for this project:

- Demonstrate and expand technical capabilities;
- Investigate use of PWM drivers in combination with AMB-technology;
- Making AMB technology available to a wider range of engineers and applications.

First, the general architecture has been described, and some of the work that was performed in order to make the module completely cable-less.

After that, several 'lessons learned' were listed, and finally some measurements were described.

This paper is written in the hope that technology described and modular design that is presented will assist and encourage engineers to use and experiment with 'off the shelf' components in general, and with Active Magnetic Bearings specific.

REFERENCES

[1] Pololu Robotics and Electronics. For "High Power 18v15 Motor Driver"-specification, see: http://www.pololu.com/catalog/product/755.

[2] HobbyPartz. For battery information, see: http://www.hobbypartz.com/batteries.html.

[3] Texas Instruments. For TMS320F28335 Data Manual see: http://focus.ti.com/docs/prod/folders/print/tms320f28335.html.

[4] Norg Consulting. For more information on this and other projects, see: www.norgConsulting.com/past_projects.html or ask Meindert@NorgConsulting.com for details.

[5] Texas Instruments. For information on "Experimenters Kit compatible with TMS320F28335 controlCARD" see: http://focus.ti.com/docs/toolsw/folders/print/tmdsdock2808.html.

[6] Digi. For X-Bee product specifications see: http://www.digi.com/products/wireless/zigbee-mesh/xbee-digimesh-2-4.jsp#specs.

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[i] Depends strongly on tooling-costs.

[ii] 15 kHz @ 100 MHz normally would equate to a 12 bits resolution, but an 'enhanced' feature allows for a 150 ns timing resolution.

[iii] The current setpoint has not been calibrated; hence its actual scaling is unknown, indicated by quotes: ['A'].