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Technology assessment for a pre-college indoor aerial robotics contest

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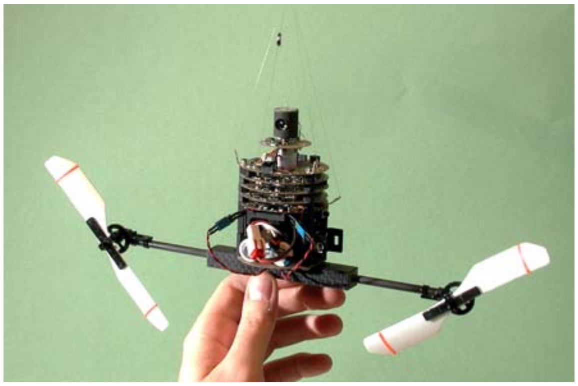

Every day, the technology improvements driven by Moore's law bring more and more professional-quality robotics within the reach of amateurs and even children. Over the past few decades we've seen this in wheeled, legged and other ground-based ("2D") robotics. Now the same forces are starting to do the same for "3D" robotics, including underwater and aerial vehicles.

The latter category, conventionally known as Unmanned Aerial Vehicles (UAVs) or, in the military, Unmanned Aerial Systems (UASs), are perhaps the most promising new frontier for amateur robotics because, unlike underwater vehicles, they don't require special access to deep water, can use conventional radio and GPS communications, and are based on cheap and ubiquitous Radio Controlled (RC) model aircraft, which are produced by a large and mature industry that is already aimed at amateurs.

Today the amateur UAVs movement has moved beyond university research teams and includes thousands of individuals around the world who are building relatively inexpensive aircraft (fixed wing and helicopters) that can fly autonomously, take pictures or videos and transmit them to the ground, follow navigational waypoints for aerial mapping and scientific surveys and otherwise duplicate many of the functions once reserved for military UAVs that cost hundreds of thousands or millions of dollars.

To encourage this, several organizations have started UAV contests[1]. Most of them are aimed at university teams, but several have started to extend that to high-school teams. These are early days, however, and only a handful of such teams have been formed. Barriers to more participation from students include cost, technological complexity and safety, to say nothing of ambiguous federal regulations governing amateur UAVs in the National Air Space.

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1 http://www.auvsi.org/competitions/

We would like to propose a UAV contest that would encourage far more participation from amateurs, especially pre-college students. It would be indoors, which has the advantage of a controlled environment for safety and no regulatory issues, and would generally follow the spirit and structure of the highly successful FIRST Robotics Competition and its LEGO robotics offshoot, the FIRST LEGO League.

The purpose of this document is to lay out the technology options for such a contest, both in standard aircraft platforms and contest area design.

Platform options:

Any aircraft appropriate for indoor aerial robotics would have to satisfy several criteria. It must be light and slow so it is safe and controllable in an enclosed area. It must be cheap (we've set a target price of $1,000) to be within the reach of student teams. It must be relatively tough and easy to repair, since crashes will be frequent. And it must be able to carry a payload of several ounces of electronics above and beyond simple propulsion and RC control, to allow for an autopilot and UAV communications.

With that in mind, the choice for indoor UAVs comes down to microlight airplanes, helicopters (single or multi-shaft), quadcopters, and blimps. Broadly the pros and cons of each look like this:

Airframe	Pros	Cons
Microplanes	Cheap, easy to fly, relatively robust.	Hard to navigate in small areas, must move to remain airborne, precise landings difficult, limited payload capacity.
Blimps	Safe, slow moving, intrinsically autonomous, can lift heavier payloads with sufficient size.	Hard to control accurately, large if carrying a significant payload, highly vulnerable to unpredictable air currents.
Single shaft (single or counter-rotating rotors) helicopters	Mature industry with many good models to choose from. Good lifting power. Very maneuverable.	Very hard to fly. Crashes tend to lead to expensive repairs. Autonomous flight technologically difficult.
Quadcopters (four rotors)	Highly maneuverable. More stable than helicopters. Good lifting power. Favored UAV platform.	More expensive than helis. More vulnerable to crashes than blimps and planes. Limited choice of commercial platforms.

We have built evaluation prototypes of all four of these. Although our research is by no means comprehensive, it was enough to draw some broad conclusions about each and to indentify the most promising technologies. In this next section we will discuss each in turn:

Microplanes

These come in two classes:

1) Tiny ultralights made with custom subminiature components that are designed to fly as slowly as possible (walking speed or slower). They're typically made with film and carbon fiber, and can fly in spaces as small as a living room.:

2) Smaller version of outdoor aircraft, typically made with foam, plastic and balsa wood and the smallest standard RC components. These fly at a running pace and require a space about the size of a basketball court:

For outdoor UAV airplanes, autonomous flight is usually achieved with autopilots that either use inertial measurement units (IMUs) that employ gyros, accelerometers and/or magnetometers, or horizon-sensing technology such as sensors that control the plane according to the infrared gradient between sky and earth or light sensors that do the same for the visible spectrum.

With indoor planes, neither will work without modification. To make an onboard IMU fast and sensitive enough for the rapid corrections needed for indoor fixed-wing flight, while still light enough for an indoor plane, is currently too hard and expensive for our price and age range.

Meanwhile, horizon-spotters won't work indoors with no horizon and artificial light. The solution there is to create artificial horizons with infrared beacons at fixed locations around the contest area and have the planes navigate relative to them.

One option in both cases is to reduce the onboard weight of the autopilot by offloading much of the processing to a computer on the ground. This devotes the onboard electronics to sensors and communications, while pushing the logic and computationally-intensive work to a place where weight is not an issue. While this is a nicely scalable solution, since you can add as much processing power as you need on the ground, it requires rock-solid and very fast communications channels. Purists might argue that it also violates the spirit of UAVs, in that the aircraft is not really a self-contained robot. We'd respond that such outboard processing is an accepted early-stage robotics technique and as long as there is not a human in the loop there is no reason why the electronics could not be miniaturized at some later date and be brought onboard.

Candidate products:

- Ultralight: Carbon Butterfly, $300[2]

- Indoor flyer: GWS Pico Stick[3]

Blimps

Blimps are a very attractive candidate because they are so safe and slow. They are intrinsically autonomous, which is to say that they will stay aloft with no human intervention. And they can maneuver well in a large room. But that docility comes at a cost. They are the least maneuverable option and as pilots of indoor RC blimps will attest, steering them is a complex process of anticipating turns long before they are to be made to counter the effects of momentum.

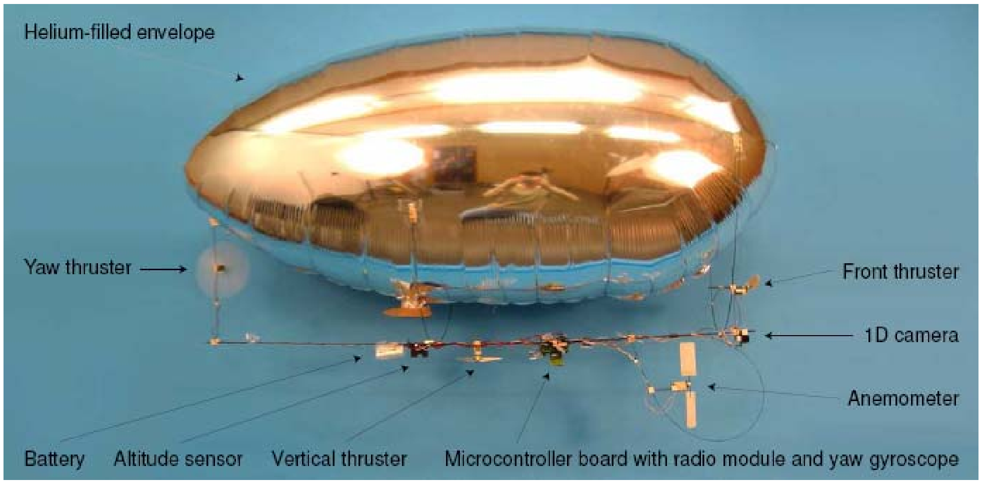
Utherane blimps, which are strong and expandable, tend to be custom-made and too expensive for our price point, so we limited our analysis to mylar blimps, which despite their fragility are at least cheap and reparable.

Perhaps the best indoor blimp UAVs were made by a team at the Laboratory for Intelligent Systems at University of Lausanne in Switzerland[4]. Their blimp, which can lift 200 grams is shown here:

2 http://www.plantraco.com/hobbies/product_carbon_butterfly.html

3 http://www3.towerhobbies.com/cgi-bin/wti0001p?&I=LXHCH6&P=7

4 http://lis.epfl.ch/?content=research/projects/microflyers/



A UK university team[5] has also built indoor mylar blimps that appear to suit these requirements well.

There are also quite a few toy/hobby blimps that can be modified for autonomous use. All of them have very limited lifting power, so weigh minimization will be a key part of the successful contest entry. This will eliminate many off-the-shelf computing packages, such as Gumstix and Lego Mindstorms NXT, and put a premium on single-board embedded processors such as BASIC Stamps and the Parallax Propeller chip. Custom circuit boards will probably also be required, which could be a useful lesson in electronics design.

Suggested platforms:

- Plantraco Microblimp ($129)[6]; good electronics but small 20" envelope; would need to be replaced by something larger for sufficient lifting power:

5 http://www.ias.uwe.ac.uk/People%20Pages/j-welsby/main.htm

6 http://www.microflight.com/Online-Catalog/R-C-Toys/MicroBlimp-RTF-Set

- "Blubberbots" from the Make Magazine Store ($99)[7]. These started as an art project[8] and are now available as a kit. They are autonomous, in the sense that they have light and touch sensors and travel towards lights and away from obstacles. But they have no positional awareness and are not programmable. The existing controller would have to be replaced with an autopilot, and a vertical thruster would have to be added. Note in the below picture that they're very safe to have around people!

Single-shaft Helicopters

Helicopters are notoriously hard to fly, but ones with two counter-rotating rotors on the same shaft are at least inherently stable. Outdoors, many people have turned RC helicopters into UAVs, but the control systems tend to be complicated and the crashes expensive. Indoors, safety and limited room for error make this even worse. Nevertheless, there are some efforts to make this work[9].

Suggested platform:

- Blade CX2 ($189) [10]

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[7] http://store.makezine.com/ProductDetails.asp?ProductCode=MKBLIMPKIT

[8] http://degree119.com/

[9] http://www.tarbox.org/helicontrol.html

[10] http://www.horizonhobby.com/Products/Default.aspx?ProdID=EFLH1250

Quadcopters

By far the best popular indoor-capable UAVs at the moment are quadcopters, which are basically four brushless electric motors with propellers pointing at the sky on an X-shaped frame. There are several university teams that have had good success with them, both as single UAVs and in flocks of UAVs communicating with each other. MIT[11] and Stanford[12] have both done work on this.

Commercial options:

- Draganfly:, $950[13]

- Silverilit X-UFO, $179[14] (best modified with an X-3D MEMS gyro controller, $200[15])

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11 http://vertol.mit.edu/

12 http://hybrid.stanford.edu/starmac/overview

13 http://www.rctoys.com/rc-toys-and-parts/DF-VTI-EYE/RC-HELICOPTERS-DRAGANFLYER-COMPARE-ALL.html

14 http://www.hobbytron.com/SilverLit-X-UFO-RC-Flying-Machine-RTR-with-4-Motors.html

15 http://www.xufo-shop.de/shop/article_17188124/X-3D-Kreisel.html?shop_param=cid%3D1%26aid%3D17188124%26

- X-3D, 839 Euros[16]

- UAVP, an open source quadcopter project, price determined by components [17]

[16] http://www.xufo-shop.de/

[17] http://www.uavp.de/index.php/de/

Contest options

Successful UAV contests tend to have a series of increasingly difficult tasks to accomplish, so that teams don't have to finish all of them to still rank. For example, a contest could provide the following challenges:

- Stage 1: Complete a square pattern autonomously (possibly through hoops)
- Stage 2: Fastest time to compete a course of pre-defined waypoints (possibly through hoops)
- Stage 3: Scavenger hunt: given one waypoint, travel to it and use real-time video to look down to see sign with key to next waypoint. Ground team observes and updates UAV with new waypoints while it's in the air. Continue for X waypoints. First to finish wins.

Contests can also have classes. For example:

- Age classes (10-12, 12-14, 14-16, 16-18)
- Cost classes (under $500, under $1,000, under $1,500)
- Airframe classes (lighter than air, fixed wing, rotary wing, flapping wing)
- Weight classes
- Effort classes (modified commercial vs. built from scratch)

There can also be limits on team size, gender composition, and number/amount of adult coaches.

Existing indoor UAV contests include a European Micro-UAV meeting[18] .

Contest Area Options

There are two main functions of the contest area: 1) establishing a safe area for UAVs to attempt certain goals, and; 2) providing position information so the UAVs can establish their location.

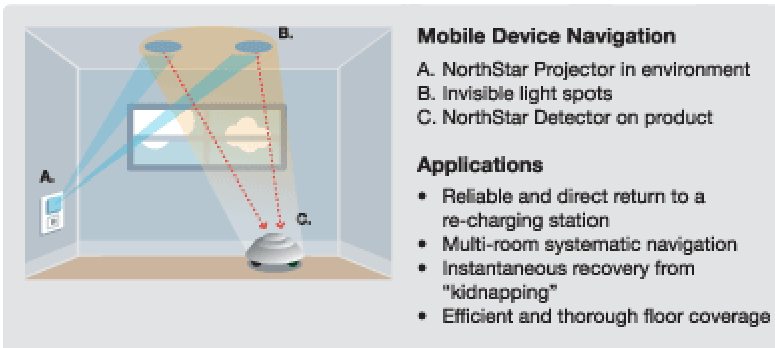
This paper has assumed an indoor space of at least the size of a high school gymnasium, with a relatively high roof and a netted-off contest area (contestants and spectators would be behind the net).

Providing position information to the UAVs:

- IR beacons: Place either three IR beacons on in the contest area and let the UAVs scan and find them and triangulate their position, or create a constellation of many IR beacons (each with a unique signature and known position) and let

[18] http://www.supaero.fr/microdrone/flights.htm

the UAVs calculate their position from whatever is in sight. The best commercial example of this is Evolution Robotic's Northstar system[19], which can either use several IR beacons in a room, or one IR projector that projects several spots on the ceiling. A low-cost and small IR receiver and processing unit onboard the UAV translates those fixed signals into a position in space.



- GPS repeaters: It may be possible to generate a synthetic GPS signal indoors by re-reradiating external GPS signals. It's not clear whether commercial re-radiators do that, or just re-broadcast the position of the rooftop antenna. Further investigation will answer this.
- Optical tracking: It is possible to mount cameras around the contest area and track the UAVs remotely, transmitting that information to the UAVs wirelessly in real time. Although this has no practical application in the real world, if it were possible to standardize this communications method it could be used in a contest. MIT has written a paper on its experience with this approach[20].
- High-sensitivity GPS/low -damping roof. Modern GPS chipsets and antennas have the ability to get signals inside under certain conditions (windows with view of sky, thin roof, etc). It may be possible to use standard GPS in such circumstances.

[19] http://www.evolution.com/products/northstar/works.masn

[20] http://acl.mit.edu/papers/GNC06_ValentiHow.pdf

Recommendations

Although any one of these options could be the basis of an indoors robotics contest with enough work, money and safety precautions, we believe that the most appropriate platform for an indoors aerial robotics contest for pre-college students is a blimp.

The primary factors in this conclusion are minimizing technical complexity and maximizing safety. Keeping a blimp aloft is not hard—the challenge is getting it to go where you want it to, which is an altogether more fun and achievable task. And there is virtually no damage that a blimp can do to either people or its surroundings—its motors are tiny, the propellers typically shielded and the body itself is simply a small balloon. Indoors, the main threat to blimps of being blown away in high winds is also eliminated.

The three main challenges that a lighter-than-air indoor aerial robotics contest will present to competitors are these:

1. Integrate electronics into the smallest and lightest package feasible
2. Triangulate IR beacon data to determine x-y-z position
3. Anticipate momentum and turn lag to precisely control a relatively imprecise vehicle

On top of that are any imaging or target recognition challenges that the particular contest may present.

If something like the Blubberbot is used as the reference platform, the students will mostly be building a CPU and sensor board and programming it; the blimp and propulsion systems are very straightforward. Part of the challenge will be in creating an appropriate test environment, and it is essential that any indoor navigation system have a development kit available with both transmitters and receivers within our target range (a few hundred dollars) so that teams can test their vehicle under contest conditions. (If there is a way to use GPS indoors, this problem is resolved)

If FIRST agrees that this sort of blimp-based contest is the way to go, we propose to build a working reference platform with a target cost of less than $1,000 and hardware components that are either commercially available today or will be within 18 months.