

Building Recreational Flight Simulators

John Michael Powell

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Preface

About fifteen years ago I was on a business trip visiting a company that made mission trainers for the US military. As an aside to the main purpose of our visit, my group was shown a non-classified demo of the mission trainer. It was a flight simulation application that was running on a high end Unix workstation. I estimate the workstation cost at perhaps \$100,000. The application allowed a pilot to “fly” over extremely realistic terrain created by overlaying satellite imagery on top of a topographic elevation mesh.

I was impressed.

Several years later I was on the show floor of the first AVSIM conference. I saw a pre-release demo of LOMAC, a flight simulation “game” that allowed the pilot to “fly” over extremely realistic terrain. I believe the terrain data was created by overlaying satellite imagery on top of a topographic elevation mesh.

I was impressed.

Of course there were some differences. The mission trainer application undoubtedly carried a price several times that of the workstation running it. LOMAC, on the other hand, would retail for about \$50, and was being demo-ed on a personal computer costing a few thousand dollars.

It’s hard to call today’s flight sim a game when it has such similarity to military trainers of fifteen years ago.

Our recreational flight simulation applications have improved to the point that a major limitation is the user interface. Personal computers are general purpose computing devices that do an adequate job meeting the needs of a broad range of applications. But,

today's flight simulation applications are capable of so much that "adequate" is not good enough.

We already augment the basic personal computer by adding joysticks, rudder pedals and engine controls. We're able to avoid the obviously not-part-of-an-airplane keyboard and mouse, at least to an extent. These basic enhancements allow us enter an illusory world of flight, if only for a few moments.

The goal is to stretch those few moments. We need to create a stronger flight illusion by building a more immersive simulator environment. We need an environment which has more elements that suggest we are indeed inside an aircraft in flight, and fewer elements that say otherwise.

But while the development of simulator applications benefits from the coordinated efforts of hundreds or thousands of talented people, developing truly immersive simulator environments has largely been an individual affair. On line communities have sprung up that provide advice, but ultimately, building a home simulator is a solo undertaking.

It's this situation that this book was written to address. It is a coordinated body of knowledge for the hobby simulator builder. It won't answer all questions; the hobby is young and new ideas are continually popping up. What it will do is provide a structure, and an overview of what is possible and where to find more information.

Mike Powell, June 2009.

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Introduction

Today's flight simulation applications are fantastic. Nonetheless, there is room for vast improvement. It's not that the applications are lacking, nor am I suggesting that you need a better video card.¹ ² It's simply that there is only so much "flight sim experience" that can be conveyed through a desktop monitor.

Think about it this way. A team of talented programmers and artists worked very hard to capture the experiences of flight and deliver them to you. Ultimately, these experiences will be played out in your mind using your PC as the delivery mechanism.

On their end they have a big budget and many specialized tools. On your end you have a general purpose computing platform, which, however expensive, is still general purpose. It is not optimized to deliver the flight sim experience.

So, what plays out in your mind is a pretty good window on the flight experience, but it's both missing some things and picking up a few unintended passengers.

In a real C-172 you use the flap lever as you prepare to land. In the simulation you use keystrokes. In the 172 you look out the left window to time your turn to base. If you turn away from the monitor you see the clutter on your desk. In the air you hear local traffic radioing their intentions. At your desk you may hear the television.

The solution to these shortcomings is to use a specialized I/O system that is optimized for delivering flight experiences. It's called a home cockpit or home flight deck.

¹ How would I know if you need a better video card? I have two daughters who are convinced I have no clue what goes on in my own household, and I don't even know you.

² Okay, actually you probably do need a better video card, and almost certainly more memory as well. Flight sim apps are designed to overwhelm the best PCs available when the products are first released. As faster PCs become available the product can then deliver more to the user. This gives the products a longer shelf life.

It's About the Flight Sim Experience

The mention of a home flight deck or cockpit may bring to mind images of incredible flight sim projects that capture with great fidelity the interior of commercial jet liners right down to the exact sun-faded color.

Don't get me wrong. There can be great joy and a huge sense of satisfaction in building a picture perfect replica of a flight deck, but it's not a necessity. The focus of this book is the flight sim experience. You don't need a picture-perfect flight deck interior to make vast improvements in your experience.

The quality of the flight sim experience depends on the feeling of immersion brought on by the illusion of flight. This illusion gains realism to the extent that distractions are removed and supporting factors are added. A home flight simulator delivers an improved experience by creating a more realistic illusion.

Component parts of a home simulator are important to the extent that they are noticed. Systems that you physically interact with the most are quite important. So, things like primary flight and engine controls are at the top of the list. Systems that command a great deal of visual attention like the primary flight instruments and the through the window views are high on the list also. Secondary controls, systems controls and indicators follow. An assortment of background elements rounds out the list.

What a component adds can be less important than what it excludes. The color of a side panel is far less important than the fact that it blocks the view of your living room carpet. It's as important to remove elements that can dissolve the illusion of flight as it is to add elements that support it.

You can imagine a continuum in the realism of the flight illusion that ranges from sitting in a noisy room looking at a picture on a computer monitor, to experiencing the real thing with all the attendant sights, sounds, smells and perceived motions. The relative importance of elements of the flight sim illusion provides the means to prioritize projects, allocate resources, schedule work, and incidentally, structure a book.

Book Structure

This book presents material about many of the important elements that go into making a home flight simulator. It's generally presented in order of descending importance to the flight sim illusion. This varies somewhat based on just what sort of aircraft is being simulated, how it might be used (i.e. IFR vs VFR), and plain old personal preference.

Chapters generally begin with descriptions of how the chapter topic is implemented and functions in an aircraft. There's often material covering functionality, appearance, and feel. There may be drawings illustrating the underlying workings. While it is certainly

not necessary to duplicate the flight rated mechanisms, it can be very helpful as you design your simulator to know how they work.

A chapter's next section presents various options for buying commercially produced equipment. There is some risk here, as commercial products go off the market all too often, while I hope that this book has a very long shelf life. Nonetheless, I think it's important to be aware of the option. Building can be a source of satisfaction, but you may not want to build everything.

There are many different ways to build sim projects. Often the "best" way is largely a matter of personal choice. It depends not only on the project specifics, but also on available resources. Chapters cover various hobby techniques. You'll find approaches using wood, plastic, metal, and various combinations. Adapt what works best for you.

The flight sim hobby spans many topics. Inevitably this means a single book which covers the breadth of the hobby can't provide in-depth coverage of each topic in a single volume. Each chapter lists references to more detailed information.

Finally, many chapters include a project. Projects are fully documented. Projects with micro controllers have commented source listings for the firmware. There are printed circuit board layouts for any electronics. The layouts are single-sided so it's easier to make the circuit boards at home. Mechanical assemblies have dimensioned drawings. And of course, the project operating principles are explained.

Appendices

I've included a few appendices that cover material that either applied to many of the chapters or is a bit too detailed to include in a chapter.

It's really annoying to build several components of a project and find that they don't fit together because the mounting holes don't line up. Fortunately, you don't have to be a machine shop wizard to make pieces that fit together. All that's required is a bit a planning and a few simple layout tools. The appendix on precision layout is an introduction on how to do just that.

Many of the book projects incorporate electronics. All of it can be built using prototyping "perf-board". Of course, you may choose to use printed circuit boards instead. If you get excited about the DIY instruments and decide to build the engineer's station of a classic B-747, having printed circuit boards is a real plus. You'll want to read the appendix on making circuit boards. Whole books have been written on the subject, so don't expect miracles. Nonetheless, you'll find a good introduction to options for having boards made professionally, and to products and techniques for making them yourself.

Micro controllers are phenomenally useful in sim building. Consider a radio control head, a typical sim project. It responds to knobs being turned, it displays active and standby frequency settings with LEDs or an LCD, and it communicates with the host computer. You can do all this with an inexpensive micro controller and a few support chips. Of course, to make the micro controller do this, you've got to be able to program the little beastie. If you've never done this, it looks like a mysterious black art. Once you know how, it's no big deal. The appendix on programming micro controllers gives you a good start to using these fantastically useful devices.

Tools & Safety

In theory all the projects in this book could be made by hand. In reality, you'll be using power tools, probably a variety of them. Please do so safely.

Please remember, the only time these projects should even be inside a real airplane is when they are in your luggage going to a flight sim convention!

Recreational Flight Simulators

Building a recreational simulator is different than building one for commercial service. Commercial simulators exist to train pilots, investigate accidents and develop new aircraft. These simulators have objective performance goals, for example, there might be a requirement to implement the exact behavior of a particular model navigation system. Recreational simulators exist to create an experience akin to flying, feelings of excitement or wonder or satisfaction. But feelings are subjective. Which factors are important in creating a flight simulation experience depend entirely upon your personal expectations. Perhaps you feel precise behavior of navigation avionics is critical; perhaps you don't.

This subjective nature leaves room for many different approaches to building a simulator, but also provides little guidance. The growth of information technology led to the creation of the flight simulation hobby. With IT's continuing growth the hobby has expanded to performance levels that rival commercial systems. A newcomer is faced with a riot of opinions, options and possibilities. The chaos can be overwhelming.

The purpose of this chapter is to provide a little order. It starts with a reminder that...

It's About YOUR Flight Sim Experience

The focus of this book is how to create an outstanding flight sim experience.

The mention of a home flight deck or cockpit may bring to mind images of incredible flight sim projects that capture with great fidelity the interior of commercial jet liners right down to the exact sun-faded color of the main instrument panel.

Don't get me wrong. There can be great joy and a huge sense of satisfaction in building a picture perfect replica of a flight deck, but if it's the experience you're after, perfection isn't necessary. You don't need a hyper realistic flight deck to make vast improvements in your flight sim experience.

The quality of the experience depends on the depth of immersion you get from the flight simulation application. Playing the application on a desktop computer creates a shallow experience. Almost anything can kick you out of the flight illusion: having to use the keyboard to control the throttle, random noise, the view of wallpaper above a too small monitor, and so on. A recreational flight simulator delivers a better experience because each of its components deepens the feeling of immersion.

A component can strengthen the experience by adding directly to the illusion or by excluding distractions. A control yoke that accurately mimics a Boeing part strengthens the experience by being a tangible item you touch and move. An interior side panel may be the precise shade of Boeing brown, but may add more to the illusion because it blocks the view of your game room carpet. You'll get the best overall results by adding both kinds of components to your simulator.

Sim building can expand to absorb all available resources, plus some. You need some way to prioritize if you're to keep this monster under control. Simulator components are important to the extent that you notice them, or don't notice what they exclude. Systems that you physically interact with most are quite important. Things like primary flight and engine controls top the list. Systems that command visual attention like the primary flight instruments and the out the window views are pretty close. Secondary controls, systems controls and indicators follow. An assortment of background elements rounds out the list. By ranking the importance of simulator components you can prioritize your efforts.

An important qualifier to prioritizing components is the word "you". A component is important to the extent YOU notice it. You're contemplating a recreational simulator so you can experience flight. Experiences are ultimately subjective. The next section lists a number of simulator components, but their relative importance is entirely your call.

In this hobby it really is all about you!

Getting Started

One of the biggest issues when starting is not having enough information to make informed decisions. You don't know what's possible. You don't know what resources are required. So you don't really know what you personally might realistically aim for. Newcomers often make their first post on a flight sim forum by outlining a rough idea for a sim then ending with an open-ended question to the tune of, "What do you think?" Usually a few helpful souls will offer a useful critique or two, but the most frequent response is to do more research.

"Research" is the right answer. It's the one I'll use to close off this section, but before we get there, here are a few thoughts on getting started.

Almost anything is possible. Hobbyists have built home simulators that rival high end commercial units. They've built motorized throttle quadrants, back-lit light plates, panoramic though-the-window displays, dimensionally accurate cockpits and flight decks, and even motion systems. Some of these may be impractical given personal circumstances, but there is no magic barrier beyond which you simply cannot go. If you've got the resources and desire, you can do it.

This is an iterative hobby. You have a lot of choices. (Build or buy? Commercial, civil, or warplane? Fixed or rotary wing? Solo or interactive flying? And so on.) You make your choices and factor in available resources (time, money, skills, available space, spousal acceptance, etc.) The pieces don't fit together. Back to square one. Or maybe just to square two. After all, you learned something the first time through, right?

Learning-while-doing is another aspect of this hobby. It's not unusual for people to "complete" a simulator then immediately begin rebuilding portions of it. Parts they had initially been satisfied with are now seen as well below their recently elevated acceptable level of quality, and newly acquired skills. By practicing on smaller projects first, you will find yourself successfully completing complex projects you might not otherwise have attempted.

So, in this anything's-possible, learn-while-doing spirit of things, here are some things to think about while planning your simulator project.

Your Expectations (a.k.a. Square 1)

A good starting point is deciding what you want from your simulator and what an acceptable cost might be. Focus on the experience you want rather than on the specific hardware and software. Saying you want to create the experiences of a short haul 737 pilot operating out of Southwest US is better than saying you want a B737-400NG simulator accurate to the CDU functionality. This gives you flexibility for choosing which simulator elements are really important when you find you don't have the resources to precisely mimic all aspects of a B737-400NG and its CDU.

Simulator Application Software

This is your first reality check. Is there an existing flight simulation application that meets your experience expectations? If you're planning on building an open cockpit biplane simulator and flying it around an animated King Kong atop a 3D model of the Empire State Building poking above a period accurate New York City, this might be a good time to take a step back.

Once you find software that will create your suitably adjusted experience expectations, make a note of its technical specs. You'll need those in a bit.

There are several good choices, including, but not limited to these. Both Microsoft's Flight Simulator X and Laminar Research's X-Plane are fine simulators. Both have many add-ons available and large user communities. Microsoft's Combat Flight Simulator 3 and Ubisoft's IL2 series offer WWII combat experiences while Ubisoft's Lock On: Modern Air Combat, Eagle Dynamics' DCS: Black Shark, and Lead Pursuit's Falcon 4.0 follow on titles offer contemporary combat flight experiences. Some of these applications are very extensible, so if you're good with animation software maybe, just maybe, you actually could add King Kong.

Flight & Engine Controls

What sort of flight and engine controls will be needed to create your target experience? If they are not commercially available, can you make them? Does your chosen simulator application support their functionality?

These controls are your primary means of physically interacting with your simulator. Functionality, feel, and appearance can profoundly impact the flight illusion and your experience. While a small general aviation sim might only have a trim switch on the yoke, a contemporary warplane with HOTAS style controls depends heavily on additional switches on the stick and throttle. If your sim doesn't support the additional functionality, it can't create as rich an experience.

Generic controls are available from several vendors. A few vendors offer controls that closely mimic flight rated controls. You can opt for the (relatively) low cost controls marketed as game controllers, or you can pursue controls manufactured with the flight training industry in mind. And, of course, you can build controls.

Visual Display System

What sort of display system will you need for viewing the world outside the aircraft?

The display system not only gives you a view of the simulated outside world, it also blocks out a portion of the real world. This is a good thing. The fewer reminders you have that you're not really flying, the stronger the illusion that you are. So, at least here, bigger really is better. The more of your field of vision that you can fill with simulated scenery (or sim cockpit) the more you enhance your experience. This is nice for all FS

applications, but is more important for some. If you're planning a combat sim, a wide field of view is a critical part of the experience. (Check your six!) Creating a sense of depth is important as well. You'll get a stronger sense of the 3D nature of the scenery if the imagery is located farther from you. A projection screen positioned 12 feet from your eyes is much nicer than a monitor at 18 inches.

A 17 inch monitor is a workable solution for some FS apps and quite lame for others. Products like the Matrox TripleHead2Go and Luciano Napolitano's WidevieW software provide the means to create panoramic views from multiple screens. The prices of video projectors are low enough that massive display systems are worth considering. Even collimated displays are edging into the realm of DIY possibility.

Flight & Engine Instrumentation

Will you need a highly accurate instrument panel? Are you building a glass cockpit, or do you prefer steam gauges? Is a computer drawn image of a moving needle adequate or will you simply not be happy until you're peering at real instruments?

Instrumentation is essential to controlling the aircraft, and it provides a large part of the ambiance of the simulator. It's constantly in your field of view, so, the more realistic the instrumentation, the stronger the illusion.

All FS applications provide instrumentation, albeit drawn on a computer screen. A quick way to boost realism is to mount the computer screen behind an instrument panel with appropriately positioned cutouts. This works extremely well when mimicking aircraft with glass cockpits, and moderately so with analog dial type instrumentation. Non-functioning, but photogenic, mockups can be used in place of less frequently referred to instruments in your simulator. This helps control overall cost while still providing a bit of illusion-supporting eye candy. Several companies sell functional instruments for simulators, although not all FS applications are capable of exporting the data needed to drive them. It's quite possible to build functioning sim instruments³. For the ultimate in realism, you can convert flight-rated instruments to simulator use.

Radio, Navigation, & Systems Controls

Are you happy to simply bore holes through the (simulated) sky, or do you want more? Does true happiness come only from operating complex radio navigation equipment, and controlling a large aircraft with multiple complex systems?

All but the simplest aircraft have secondary systems. In general aviation, it might be a basic communications transceiver. Commercial aircraft have navigation receivers, computers, transponders, autopilots, and fuel management systems. Military aircraft add surveillance gear, targeting and weapons systems. These systems do not command your

³ Shameless plug: see my book, [Building Simulated Aircraft Instrumentation](#) available from Mike's Flight Deck Books. (www.mikesflightdeckbooks.com)

attention 100% of the time, but they are a part of the experience. To the extent that you can support them in your simulator, you will have a more immersive environment.

A few companies offer modules for controlling sim radios. There are a few offerings of simulated CDUs, and even an offering of a HUD. There are companies and individuals offering back lit panels for commercial transport aircraft and for a few select warplanes. You can convert retired aircraft control panels to simulator use. It's likely you will be building some or all of this gear from scratch.

Interfacing Hardware & Software

If you choose to build controls or annunciators, can you connect them to your simulation computer? Will the FS application exchange data with them?

This is an important bit of behind the scenes scaffolding. It's certainly a step up to add realistic switches, knobs, and annunciator panels, but it is outstandingly wonderful to have the simulator respond when you flip those switches and twist those knobs.

One of the least expensive approaches to interfacing switches is to use the electronics from a USB gamepad. This will provide as many as a dozen switch inputs. Since the software is already in place, all you need to do is configure your simulator application to respond to the modified gamepad. You can also buy generic interface modules that come with their own driver software. And, of course, you can build your own interface hardware, and write your own software for the ultimate in flexibility.

Sound

Do you lust after engine noise? Will you chat with squadron members, or ask for ATC clearance?

Sound is a nice boost to simulator ambiance. It supports the flight illusion by adding aircraft specific sounds, and by blocking out distractions. It can also be a method of direct interaction. A number of simulator applications incorporate or support add-on speech-related applications. You might use speech recognition software to interact with applications on your own computer. You might also use VoIP⁴ applications to interact with others across the Internet.

Your computer quite likely has most of what you need, a sound card and a pair of speakers. You might need to buy a microphone, although a headset incorporating a microphone is probably a better choice. The headphones will provide isolation from room noise. If those sharing your living space don't mind too much, consider connecting a beefy sound system to your sound card to create a sonic ambiance you can feel.

⁴ VoIP stands for voice over Internet protocol. Applications like RogerWilco, Squawkbox, and TeamSpeak use VoIP to support voice communication between people engaging in shared flight simulation activities.

Enclosure

How much isolation do you need from the world outside your simulation? (How much isolation does the world need from you?) Are headphones and a large display enough or do you need a partial or perhaps even a full enclosure to block out distractions? Do you have the room, money and support to install the needed enclosure?

An enclosure is the backdrop of your flight simulator stage setting. It sets the tone of the illusion and provides isolation from real world distractions. Depending on your personal preferences, it can be frivolous gold plating, or an essential part of the experience.

From time to time small companies will pop into existence to sell very basic enclosures. They're little more than visual blinds. They don't offer much substance to the flight illusion, but do serve to block visual distractions. A few companies offer enclosures, or enclosure kits, which offer more visual realism. You can build very realistic enclosures using scaled up model airplane building techniques. For the ultimate in realism buy aircraft salvage and convert it to simulator use.

Motion & Force Cueing

Should a simulator feel as though it is moving? If you feel it should, does your chosen FS application export the needed motion data with a sufficiently small latency?

The seat-of-the-pants sensations generated by an aircraft in motion telegraph acceleration, turning, turbulence, weapon release, and runway bumps, along with a host more things. Simulating these sensations adds more depth to the flight illusion, enriching the experience.

Most motion sensations cannot be truly replicated on the ground. Even massive 6-DOF (degree-of-freedom) simulators only produce onset cues. Producing a full set of good onset cues is difficult and costly. It involves moving a heavy simulator cabin in close synchronization with the external imagery and the movement of the flight controls. That said, there are approaches you can take, and some are actually cost effective.

You can use a tactile transducer to create thumps and bumps for your flight experience that signal weapons release or rolling over cracks in the taxi way. You can use it to mimic shaking caused by turbulence or engine operation. You can couple the thumps, bumps and shakes into the seat and the flight controls. If you've got the money and inclination you can even buy or build a motion base for use with your simulator. It doesn't have to be a 6-DOF motion base. You might be concerned only with pitch and roll. It doesn't have to be true to the simulated motion of the aircraft. Remember it's an illusion you're creating for yourself. It's good if it adds positive elements to your experience.

Back to Square 1?

At this point you should have a good idea of the major topics to consider when planning a recreational flight simulator. Probably not the answers, though. There's a lot of material, but if you've got a good list of questions you're off to a good start.

Do some research. The last few pages have only hinted at what's possible. You need more detail. This book is loaded with detail and there is a vibrant flight sim community of talented and innovative people. Involve yourself in it by visiting forums and hobbyists' project websites. Both offer a wealth of freely shared knowledge. The last section lists a number of major forums with particular interest in DIY recreational simulators.

You also need to determine what's practical. Factors like time, money, and available space certainly figure into this, but so too do skills and tools. The next section lists a number of useful skills, the basic set of tools needed to exercise those skills, and what sorts of projects you might accomplish at differing skill levels.

Once you've done some research, head on back to square 1 for another pass through the topic list. See if the pieces don't fit together a bit better.

Useful Skills & Tools

Skills required to even contemplate starting a worthwhile DIY flight simulator that won't embarrass your family include PhDs (or equivalent job experience) in computer science, electrical engineering, mechanical engineering and industrial engineering. An undergraduate degree in human factors with a focus on ergonomics is useful (though not critical if you have a good chiropractor). Completing two or more deployments in a nuclear submarine as Reactor's Mate 1C is also desirable as it builds the discipline so you always do the right thing the first time. If a medium size tool and die shop is not readily available a small shop will suffice as long as you have four or more years experience in furniture making, machining, welding and sheet metal.

At least, that's what you might think after looking at a few of the more accomplished hobby projects. The reality is much happier. Basic skills will get you a long way, and you can (will!) learn new skills as you progress with your simulator.

A sobering caveat, however: if you run across a website showcasing a recreational flight simulator that makes your eyes pop out because it looks like it cost half a million dollars and was made by someone who owns a machine shop, quite likely it did and he does. If, on the other hand, gazing on the simulator only results in you drooling on yourself as your jaw drops open⁵, chances are it was lovingly made by one of us, a hobbyist who learned a few new skills while pursuing his passion.

⁵ We flight sim folks are sensitive, emotional people who often display our feelings in public.

Here's an only slightly opinionated view of what skills and tools are useful in sim building, and what sorts of projects you might accomplish with different skill levels.

Woodworking

Wood is such a versatile, inexpensive, readily available material that at least a little woodworking skill is highly desirable. The simulator may depend on high tech hardware and software, but the quality of the flight illusion depends on bringing all the components together into a unified whole. Wood is a wonderful material for holding those components, and it's not a bad material for making some of them.

A common approach to building an airline flight deck is to make the main instrument panel, the center console and the glare shield from wood. LCD monitors mount behind cutouts in the instrument panel. The improvement to the flight illusion compared to a bare monitor is striking. Wood can be shaped into control yokes or stick grips, a fact that the project in the Control Yokes chapter demonstrates. Wood is a good material for making complete enclosures. Using techniques similar to those for making model airplanes, hobbyists have built fighter cockpits and airliner flight decks.

The needed skill level is not all that demanding. You're not making fine furniture, you're building a stage set. You need solid construction. An initial finish that's a bit rough isn't a problem. Polyester filler covers a great many sins. A little sanding, a few coats of paint, and you're golden.

In theory all the woodworking can be done by hand⁶. In reality, power tools rule. It is far more fun to have something with a motor do the cutting and sanding. If you're only going to buy one power saw, go with a handheld jig saw. Its narrow blade will allow you to make curving cuts. If used with a guide, you can make decent straight cuts. Swap out the blade for one with more teeth and you can cut metal with it.

A small belt sander is a good choice for a single power sanding tool. With a rough grit belt it's good for dressing edges and rounding corners. It's pretty good smoothing surfaces when loaded with a fine grit belt. You won't be able to get into tight corners with it, but it's a good all around tool.

An electric drill has great utility, particularly so if you also have drill bits. Wood pieces invariably need holes in them. Usually lots and lots of holes. As an added plus, chuck a screw bit in your drill, and wood screws go in much easier.

⁶ The pyramids were built before electric power tools, and just look how big there are! The projects in this book are small, actually miniscule by comparison, and they're not made of stone, either. They shouldn't take any time at all. Even moving forward to more modern times (i.e. AD instead of BC), the great cathedrals of Europe were built before electric power tools, and they had windows! Of course, I don't think the builders of either particularly enjoyed themselves. In fact many never lived to see the projects finished so you'll be using power tools. Just do so carefully: Read the instruction manuals.

My fascination with power tools is no excuse not to mention that you actually will need a few non-power tools. Like clamps. You can't have enough clamps⁷. You'll need to clamp work down while you're doing power tool things to it. You may want to clamp wood together while glue's drying. Start with a few bar clamps, and work your way up.

A tape measure, a framing square and a hammer are also useful.

Larger power tools like table saws and radial arm saws are certainly useful, but not required.

Metalworking

Some things are better done with metal than with wood. Metal's strength makes it a natural choice for brackets and frequently used (and abused) mounting flanges. The projects in the DIY Instruments chapter rely heavily on sheet aluminum and aluminum spacers for their structure, while the project in the Pedals chapter is made from mild steel tubing and off-the-shelf bolts. The occasional, artistically shaped bit of gold or silver when presented to your spouse can have a profoundly positive impact on your simulator progress and longevity. Metal has broad appeal.

The key metalworking skills are layout, cutting, and drilling. Layout is simply drawing on the metal work piece so you know where to cut and drill. Precision layout is not difficult and is covered in an appendix. Cutting can be done by hand or with power tools. Drilling is most frequently a power tool activity.

A marking gauge, a scribe, a steel rule, (possibly) an inexpensive 6" digital caliper, a center punch, and a small hammer are the basic tools for doing layout.

The hacksaw is the quintessential metal cutting tool. Even if you have metal cutting blades for your electric jigsaw, a hacksaw should be nearby. Sheet metal snips or shears may not be the best tool. Having said that, there are a few projects where they are useful. Although the DIY instruments have sheet aluminum components, snips and shears distort the metal. A better approach is to clamp the sheet aluminum securely and use a jigsaw to cut it. You can finish the edges with a file.

The preferred tool for drilling holes in metal is an inexpensive, bench top drill press. Using a hand power drill is marginal at best. It is difficult to accurately position the bit, and can be dangerous when the work piece is not clamped down.

Welding gear, gas or electric, provides a means to fabricating complex structures and linkages. If you've got the gear, certainly use it. If not, not to worry, there are alternative approaches. Metal can often be fastened with bolts or adhesives. The Pedal chapter shows how to make a steel pedal set without welding.

⁷ Well, maybe you can, but I haven't gotten there yet.

Electronics

It pains me to admit this, but you can accomplish a great deal in this hobby without knowing much about electronics at all⁸. If you buy commercial interface hardware all you need are basic wiring skills to connect switches, LEDs, and potentiometers. The hardware normally comes with instructions, and often with a link to an online support forum. You'll need some basic tools: screwdrivers, needle-nose pliers, wire stripper, and a soldering iron.

It's worth spending a little extra for a quality soldering iron. It doesn't have to be a fancy one with a variable temperature control, but it should have a replaceable tip. The cladding on the tip will eventually wear through, the exposed metal will oxidize and solder will cease to properly flow onto it. You'll spend half your time cleaning the tip. It's better to just replace it at that point. And, of course, the higher quality tips tend to last longer anyway.

Hardware hacking requires a slightly higher skill level. This can be a cheap way to add to your simulator. For example, you can use the electronics from a game joystick or gamepad to interface flight or engine controls to the simulation computer. You'll have to replace the switches and potentiometers with connections to the switches and potentiometers in your simulator. Generally documentation will be in short supply, so you'll need to be able to disassemble the unit, identify components, trace out connections on circuit boards, and have a general idea of what the to-be-hacked hardware does.

You can hardware hack using the same tools used for wiring.

Building electronics from scratch isn't much more difficult. It helps if you can make circuit boards⁹, but it's not a necessity. There are several companies that make circuit boards at nominal cost. Actually, circuit boards aren't a necessity either. All the electronic projects in this book can be built on prototyping "perf-board". This works just fine. Circuit boards look nicer, and build time using them is shorter if you're making several copies of something.

A digital multi-meter (DMM) is a helpful addition to the basic tool set. Building from scratch is more involved and has more opportunities for things to go wrong. A DMM is useful for checking if power is getting to where it's supposed to go. It's also quite useful for checking the resistance of components. The color rings on resistors that indicate the value get smaller every day. It's hard for some of us older folks to be sure of the color when the rings appear to be the size of the period at the end of this sentence. Double checking the resistance value with the DMM can reduce heartburn later on.

⁸ I spent a good portion of my career waxing poetically about the wonders of electronics. (I actually did a few electronicky things too.)

⁹ There is an appendix that overviews both making circuit boards yourself, and locating companies which can make them for you.

A magnifier is also helpful. I'm not referring to a five-inch Sherlock Holmes style magnifying glass, good for show and not much else. I'm talking about an eight or ten power, compound lens magnifier. Most problems encountered while building electronics are due to assembly errors: bad solder joints, incorrect parts, chips installed backward, shorts between circuit board traces, and hair line cracks in those traces. A meticulous inspection with a magnifier before applying power to a newly built circuit can both reduce heartburn and lower blood pressure.

Making significant modifications to working circuitry and developing new designs require more than a casual acquaintance with electronics. You'll need to know something of the principles of electronics: voltage, current, Ohm's law, logic, and so on. That said, you don't need to be able to design the next processor for Intel®. The vast majority of home-grown circuitry in simulators sprouts from simple applications of basic data transceivers, small micro controllers, voltage regulators and the occasional logic gate. Pursuing the hobby with this level of involvement will require several dozen hours in background preparation, and an acceptance that some of the magic smoke will escape from your projects no matter how careful you are.

Working with micro controllers requires a device programmer. This is a little interface module that you use to load the program into the micro controller. While you can build a programmer, it's no more expensive to simply buy one, and you get the added benefit of firmware updates from the chip manufacturer. Several projects in this book use Microchip micro controllers, and were programmed using the inexpensive "PICkit 2" device programmer purchased directly from Microchip.

There are a number of Internet-accessible tutorials to help you get started. For example, take a look at the Sparkfun Electronics site. (www.sparkfun.com)

Practical Electronics for Inventors by Paul Scherz is a good reference to have around. It can be a little intimidating until you realize you don't have to read the whole thing. Twenty to thirty pages cover the basics. The rest of the book serves to answer specific questions when you get into more advanced project work.

Micro controllers deserve special attention. They are extremely useful devices for adding all sorts of simulator functionality for not very much money. They're great for giving local intelligence to modules like radio heads, CDUs, and autopilots. Their use allows these modules to respond instantly to pilot input without impacting the frame rate of your simulation application. Myke Predko's Programming and Customizing the PIC Microcontroller is an outstanding tutorial. If you're already a computer whiz you can get by browsing the documentation on the manufacturer's website. If you're new to micro controllers, buy the book.

Computer Knowledge & Programming

You've installed your flight simulation application, and gone through multiple configurations to get it just the way you want it. There's a good chance that you've also installed add-ons like scenery or new aircraft. You're reasonably computer savvy.

Your current computer knowledge is all that's needed to install a number of commercially available hardware interfaces. You might use this sort of interface to connect a homebuilt joystick, throttle quadrant, or an annunciator panel. Some of the interfaces will use generic device driver software within Windows. They will appear as generic game controllers to the flight simulator application, and can be configured with the application utilities. Other interfaces come with their own configuration software. In either case the process is no more difficult than what you've already gone through configuring your flight simulation application.

With a bit of text editing, you can make significant changes in the operation and appearance of the flight sim application. Within MS Flight Simulator, the parameters that describe aircraft performance are stored in a text file. Edit the file, and you change the aircraft flight model. Other text files store the layout of the instrument panel. Learn the file format and you can move the instrument image locations on your monitor to match holes cut in the physical instrument panel of your simulator. Hang the monitor behind the cutouts, and your sim's just taken a set up in realism. This is a bit more involved than configuring the FS application, but not by much. The file formats are well documented and publically available.

So far these changes haven't added new capability to the FS application. They've simply tweaked and rearranged existing functionality. To add something truly new, you must take a step toward programming.

Starting with FS9 Microsoft began making heavy use of XML (extensible markup language) to define and control the operation of the instrument panel gauges. Arguably, XML is not a programming language, only a text schema for describing something. However, as used in MSFS, XML has variables, arithmetic and logic operators, and conditional statements, so you use it as you would a programming language.

If you can logically describe the behavior of an aircraft instrument, you can use XML to build a virtual gauge for use in FSX. You'll also need to create (or import and modify) the images that comprise the visible gauge elements, so you'll also need some skill with drawing and image editing software. The XML for a single pointer gauge like a fuel gauge is only a little tricky, primarily because of XML's use of reverse polish notation. More complicated gauges require somewhat more complex XML. Actually, that's a vast understatement. Just trying to read the XML for a complex gauge like a GPS unit will make your eyes burn and your neck ache, but that doesn't change the fact that by using XML and an image editing application you can create a wide range of new functionality within FSX. With a little practice you'll be making complex gauges with minimal neck ache, though your eyes may still burn a bit.

The XML used to create MS FSX gauges is documented in the Microsoft Flight Simulator X SDK (system developer's kit). The SDK ships with the deluxe version of FSX and is updated from the FS Insider website.

If you take three full steps into the programming world, you can work some real magic.

By using a high level programming language, accessing the FS application through software and calling on utilities provided by the operating system you can add arbitrarily complex functionality to your simulator. A high level programming language is something like Visual C++, Visual C#, or Visual Basic. These are powerful tools that require some effort to become familiar with.

A programming language by itself is not enough. You must also have access to the FS application from your program. Not all simulation applications provide this capability. Microsoft FSX has an API (application programming interface) called SimConnect. X-Plane similarly provides an API. A few otherwise impressive simulation applications, sadly, offer only primitive interfacing capabilities.

Developing your own program to exchange data with your simulation application is just the start. You also must do something with that data, and that often means talking with the operating system. For example, if you want to develop a HUD (head up display), you'll need to call on the graphics capability of the operating system, such as Windows GDI+ or DirectX¹⁰. If you want to interface with external hardware, you'll need to call upon a hardware resource like the serial port.

The necessity of concurrently wrestling with three aspects of computer programming makes this approach more challenging than the initial FS application configuration, but the payoff is greater. While the needed skill level is higher, it's not out of reach. You don't need to be software wizard, only a moderately successful amateur.

There are a number of free programming resources. The express editions of Microsoft compilers are available as free downloads from the Microsoft Visual Studio website (www.microsoft.com/express/vwd). The site includes links to assorted tutorial materials such as "Coding4Fun", a blog with a never ending series of sample software projects. Documentation and tutorials covering SimConnect are part of the MS Flight Simulator X SDK.

Communication

There is a large and growing hobby flight sim community. Many of the problems you will face have been solved. Good communication skills let you tap into that accumulated flight sim wisdom using forums, instant messaging, VOIP apps, and email.

¹⁰ You could alternatively use a third party graphics library like OpenGL. There's more about that in the Computer Drawn Instruments chapter.

The Hobby Flight Simulation Community

The flight sim community is your best resource¹¹. The easiest way to connect with the community is to participate in one or more of the online flight simulation forums.

Avsim hosts news, reviews and forums for the hobby flight simulation community. The Avsim “MS FSX Simconnect Forum” addresses topics related to Microsoft’s proprietary API for programming against MS Flight Simulator X. “The Home Cockpit Support Forum” addresses just the topics you would expect. (www.avsim.com)

Check-six! is a French-language site with news, articles, and forums related to flight simulation. Of particular interest to recreational flight sim hobbyists is the “Cockpit & mod perso” forum. (www.checksix-fr.com)

Flight Deck Solutions is a Canadian company which manufactures and supplies components for flight simulators. The company operates a small forum primarily for its customers. There is, however, an area within the forum dedicated to open discussion. (www.flightdecksolutions.com)

FlightSim.com is one of the largest, if not the largest, flight simulation sites. It presents news and features ranging from reviews to tutorials. It hosts an archive of “how to” articles of interest to sim builders, as well as, a number of forums. The “Cockpit Builders” forum collects threads on interest to recreational sim builders. (www.flightsim.com)

Frugal’s World maintains a broad range of simulation forums including the Home Cockpit Building forum. (forums.frugalsworld.com)

FSDDeveloper.com is a high powered technical site for those drawn to the inner workings of Microsoft Flight Simulator. One of the FSDDeveloper forums centers on SimConnect, the API for interfacing with MS Flight Simulator X. (www.fsdeveloper.com)

FSNordic hosts an active Finnish language Home Cockpit Forum (www.fsnordic.net)

Hovercontrol is a watering hole for the helicopter flight simulation community. There is a “Home Cockpits and Hardware” forum for the recreational sim builder. (www.hovercontrol.com)

MyCockpit is the largest, most active English-language forum dedicated to the construction of recreational flight simulator. (www.mycockpit.org)

PitBuilders.Fr is a French language forum dedicated to home cockpit building. (www.pitbuilders.fr)

¹¹ Excepting this book, of course!

SimFlight flight simulation news hosts forums in several languages. The English-language “simFlight’s Cockpit Builders Forum” covers DIY sim construction. (www.simflight.com)

SimHQ serves the gaming simulation community by providing articles, and news, as well as, supporting message forums. The SimHQ Pit Builders forum addresses hobby built simulators and simulator components. (www.simhq.com)

The Viperpit.Org forum is a meeting place for a very detail-oriented builder community tightly focused on building Falcon F-16 simulators. A number of the members have individually concentrated on specific portions of the simulator, created high quality components, and made them available to the community at nominal cost. You’ll find accurate reproductions of knob sets, dimensionally accurate drawings of the F-16 cockpit, and back-lit panels that appear identical to the flight-rated items. (www.viperpits.org)

Don’t forget manufacturer’s sites. FSInsider is the community outreach site of Microsoft Game Studios. While not a forum, it does offer articles and posts by MS insiders. It’s a good place to check for updates and it provides links to several Flight Simulator team member blogs. (www.fsinsider.com)

Ubisoft publishes the Lock On: Modern Air Combat series of combat flight simulators. The Lock On forums are mostly concerned with generic community help issues: bug reporting and user confusion. Occasionally, topics relevant to cockpit building will surface. (forums.ubi.com/eve/forums)

Eagle Dynamics, the developer of the Lock On series and the Black Shark combat helicopter sim, hosts an English and Russian-language support forum. This is another place to meet and interact with knowledgeable people. (forums.eagle.ru)

X-Plane.org hosts a small forum supporting the X-Plane flight simulator application. As with the Ubisoft forums most threads relate to resolving confusion and discussing bugs. Even so, this is where the X-Plane gurus hang out, and if you have questions about using X-Plane in your homebuilt flight deck or cockpit, this is where you should ask. (forums.x-plane.org)

Another way to contribute to the flight sim community is to document your own progress on a website. Posting lots of pictures and clear explanations will help others as they begin to research their project options.

Joysticks

The “flight control stick”, “cyclic”, “joystick” or simply “stick”, in one form or another, has been a key element of aviation from the beginning. It has been, and continues to be, a central element in a pilot’s ability to control an aircraft. As fixed wing aircraft grew larger, the stick was replaced by a yoke. We seem to be coming full circle, however, as fly-by-wire becomes more common. Yokes are giving way to an updated stick in the guise of the side stick controller.

This chapter begins with an overview of the joystick in aviation. If we’re to simulate a joystick with enough fidelity to add realism to a simulation we need to understand the functionality, look, and feel of the real thing. There is material on control loading, the methods of producing forces on simulator joysticks that mimic the forces on aircraft joysticks in flight. There is a list of purchase options. Although much of the flight simulation hobby involves building, it’s sometimes more appealing to buy an item. You can’t make a good build versus buy decision without knowing what’s on the market. The chapter concludes with a project: a floor mounted cyclic.

Joysticks in Aviation

A high quality flight simulation experience requires a compelling flight illusion. The simulator joystick has a central role in creating and maintaining that illusion¹². You physically interact with this joystick continually. If it has the right look and feel, the appropriate buttons and switches, it becomes a statement to the “reality” of the illusion. Ideally it becomes so “real” that it fades into the background and you become lost in the illusion of flight.

¹² Well, at least it does if you’re simulating an aircraft that has a stick.

General Characteristics

As aircraft have become more complex, the role of the joystick has expanded beyond simply controlling pitch and roll. The joystick has become home to assorted system control switches. It's common to have aircraft trim and push-to-talk switches on the grip. There may be weapon systems switches, hoist release buttons and so on. The presence and functionality of these switches can be critical to developing a solid flight illusion. When simulating a warplane, you really don't want to use a keyboard to launch a missile.

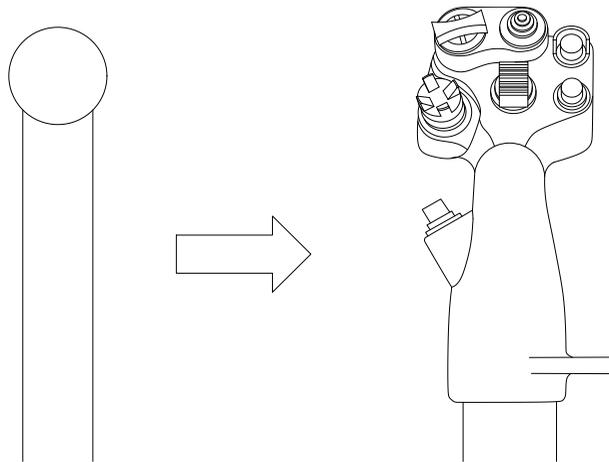


Figure 1. Joysticks have evolved.

An aircraft joystick has a unique flight feel to it. As the pilot pushes and pulls, it resists and moves in ways that are characteristic of the particular aircraft and perhaps also of the specific flight conditions. A joystick in a small general aviation plane does not feel like a cyclic in a helicopter, and a side stick controller in an F-16 does not feel like a side stick controller in an Airbus. Most game joysticks incorporate springs to provide a proportionate centering force. This is a workable approach, though it is rarely characteristic of real aircraft. Duplicating realistic stick forces moves your simulator a step up the realism continuum.

Range of motion and the path followed within that range are also aspects of joystick feel. Most game joysticks are stubby affairs that pivot directly below the grip. This is may be okay if you're simulating an aircraft with a side stick controller. Helicopters and many combat aircraft, however, have floor mounted joysticks. This positions the pilot's hand differently than would a side stick controller, and the greater length of the floor mounted stick results in larger hand movements. Giving your simulator joystick the same motion adds realism.

Flight controls in military and commercial aircraft are solidly built and they feel that way. A cast aluminum flight grip will be at the ambient temperature when the pilot first grabs it. It is some time before it warms or cools to the pilot's hand. Contrast this with a plastic game joystick sliding on a table top. It may talk to the computer, but what does it say to you? Robust construction and temperature are subtle factors, but still worth consideration if you're striving for extreme realism.

Aircraft are new for only a short time. Commercial aircraft, and military aircraft in particular, are used hard. Paint wears. Metal shows though. Upgrades, repairs, and modifications rarely leave a showroom appearance. Along with the cockpit interior, the joystick appearance creates the mood when you enter the simulator. A joystick with a worn appearance, perhaps sporting an obvious modification, can be an asset when creating the illusion of a real-world aircraft.

Some joystick characteristics are easily researched. Cockpit pictures and pilot manuals will give you an idea of the flight grip appearance, the presence of switches and their function. You'll know if the aircraft has a floor mounted joystick or a sidestick controller, so you'll have a good idea of its range of motion. The stick forces experienced by the pilot in flight may not be so easy to come by. You may have to make some educated guesses based on aircraft type and a little aerodynamic knowledge.

Joystick Flight Feel

Joystick flight feel depends on whether the aircraft is fixed wing or rotary wing. It depends on whether the aircraft has a force assist servo between the stick and the control surfaces, or if the pilot experiences the aerodynamic forces on those surfaces through the flight grip. It depends on whether the joystick is motion activated or force activated.

If research doesn't uncover specific information for the aircraft you're simulating, the following material will help you simulate flight feel that is at least characteristic of the aircraft type.

Basic Stick

Small general aviation aircraft and many older military fighters have manual flight control systems. The pilot uses a "basic stick" without any hydraulic or electrical assistance to fly the plane.

The basic flight control stick is a lever that provides the mechanical advantage necessary to move the aircraft flight control surfaces during flight. The stick might be connected to the control surface through cables, torque tubes, pushrods or a combination of them. Whatever the method, the connection works both ways. The stick lets the pilot push the control surfaces against the air. The air pushes back.

When the aircraft is sitting in still air there are no aerodynamic forces acting on the control surfaces. The pilot need only apply enough force to the stick to overcome any

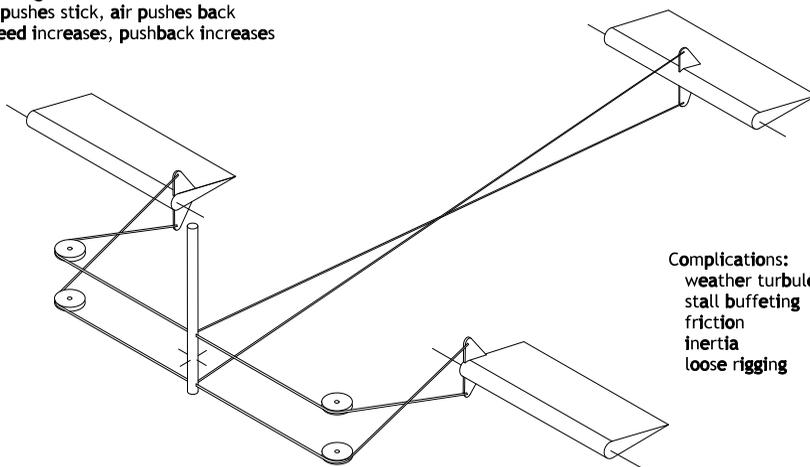
friction and mass imbalances to cause the controls surfaces to move. That changes as the plane begins to move. With air sliding over the wings, aerodynamic forces come into play. At low speeds these forces are small. The pilot finds it easy to move the stick, and the effect on the plane's motion is small. The stick feels "mushy" and it takes large stick movements to control the plane. At high speeds, aerodynamic forces are large. The stick feels firm, and much smaller stick movements command rapid responses from the plane.

The air does not always move smoothly over the control surfaces. Turbulence can shake the plane and that will be felt through the flight controls. Buffeting from an impending stall can also be felt. In fact, during a stall, air flow over some control surfaces can be so altered that the controls feel totally different.

Friction adds another component to the stick feel. The linkage between the stick and the control surfaces may include cables, pulleys, torque tubes, bell cranks, and push rods along with assorted bushings, bearings and fairleads. Each has its own contribution to stick feel. Cables drag on fairleads, bushings become dusty and bind, bearing grease cakes, and so on. In (well maintained) small general aviation aircraft friction is a small factor. As aircraft grow in size, friction becomes a larger component.

Basics of flight control feel:

pilot pushes stick, air pushes back
airspeed increases, pushback increases



Complications:
weather turbulence
stall buffeting
friction
inertia
loose rigging

Figure 2. Factors in flight control stick feel.

Inertia also comes into play. This is the characteristic of mass that requires a force to get it moving and an opposite force to slow it down. In larger aircraft with heavier control surfaces and control linkages, inertia tends to slow the control response. Part of the force the pilot applies to the stick is required simply to get the controls moving before the pilot begins to battle with whatever aerodynamic forces the control surfaces may encounter.

Aircraft rigging adjustment will affect the stick feel. Loosely rigged control cables will impart sloppiness to the stick feel. Overly tight control cables will accentuate any friction in the rigging leading to sticking and hard to move controls.

Helicopter Cyclic and Collective

Rotary wing flight control feel is very different than that of fixed wing aircraft. The aerodynamics are different and all but the smallest helicopters incorporate hydraulic servos that isolate the controls from the rotors.

The rotor on a helicopter requires two separate control sticks. The collective control stick (or simply “collective”) is a lever mounted to the left of the pilot’s seat. Raising the collective causes an increase of pitch of all the rotor blades. This controls the total lift from the rotor. The collective generally has a twist grip that acts as the throttle. Often there is a switch box at the end of the collective lever which houses a variety of controls depending on aircraft model.

The cyclic control stick (or simply the “cyclic”) controls the change in pitch of the blades as they rotate. If the blade pitch is higher on one side than the other, the rotor disk will tilt forward and the helicopter will move forward. The 90 degree difference between pitch movement and rotor disk tilt is due to the gyroscopic nature of the spinning rotor. The cyclic is situated between the pilot’s knees. It’s often curved to bring the grip closer to the pilot.

The cyclic grip generally has an assortment of switches on it. Flying a helicopter requires a great deal of attention. Having switches on the ends of the cyclic and collective places them close at hand.

A helicopter pilot does not feel aerodynamic forces on the control stick as a fixed wing pilot might. The rotor is always spinning at roughly 400~500 RPM regardless of airspeed, and the blades are continually changing pitch. A small helicopter will reflect this as a vibration in the cyclic that changes with the rotor RPM. Larger helicopters have hydraulic actuators that isolate the controls from the rotor dynamics. As a result the pilot of a large helicopter feels little or nothing through the controls.

Some larger helicopters have an adjustable spring centering system on the cyclic. (For example, the Bell-TeXTron force gradient trim system.)The system consists of a pair of springs and a pair of electrically activated clutches. One spring and clutch assembly will center the fore and aft motion of the cyclic. The other assembly will center side to side motion. A switch on the cyclic grip allows the pilot to control the clutches. With the system turned off, the pilot can move the cyclic with no spring force being applied to it. When the system is turned on, the clutches lock and the springs exert a centering force around the then current cyclic position.

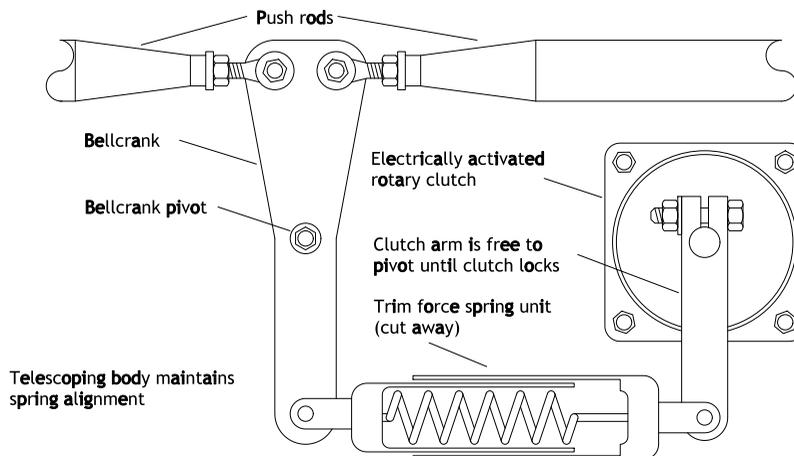


Figure 3. Cyclic spring force trim assembly, one of two axes.

Commercial Service Sidestick Controller

Computerized flight control systems enhance stability, increase fuel economy and boost safety. In some larger aircraft the pilot no longer controls the aircraft directly, instead, though fly-by-wire he controls the system that flies the aircraft. With no requirement that the flight controls provide the mechanical leverage to move large control surfaces, fly-by-wire controls are designed for comfort and convenience. The Airbus sidestick controller (SSC) is representative of commercial service sidestick controllers.

Airbus produced the first fly-by-wire commercial air transports. Designers chose SSCs in place of the yokes which were the standard of the time. The SSC provides input to the flight control system which in turn operates the flight control surfaces. The system implements control laws, software which interprets pilot actions based on current flight conditions and a set of rules meant to ensure safe operation of the aircraft. For example, one rule restricts attitude to no more than 15 degrees nose down. Even if the SSC grip is held full forward, the flight control system will not move the control surfaces to drop the aircraft pitch below -15 degrees.

The SSC does not provide the pilot with any direct feedback of the aerodynamic forces on the control surfaces. Instead, the pilot feels the forces developed by springs and damping elements as he moves the SSC grip. The pilot receives indirect feedback though the resulting changes in the aircraft behavior.

Military Service Sidestick Controller

One of the great disadvantages¹³ facing a modern fighter pilot is the fact that it is quite difficult to move during a high-G turn. When you weight several times your normal weight, it's hard enough to keep from blacking out, much less move the flight control stick several inches this way then several that way. The solution implemented in the Falcon F-16 is that the stick moves hardly at all. It's force activated.

The Falcon SSC is not mechanically connected to the control surfaces. Electronic sensors¹⁴ measure the forces the pilot places on the SSC and relay those measurements to the flight control computer. The computer commands servos that have the task of moving the surfaces. As in the Airbus, this means the pilot receives no feedback through the SSC about aircraft flight conditions. Effectively, the Falcon SSC grip is connected to the airframe through a very stiff spring. The stick moves just enough to provide the pilot with basic tactile feedback.

Which Joystick Characteristics to Simulate

Simulate or mimic those joystick characteristics that make a difference to you in your simulator. Consider functionality, appearance, and feel to determine what aspects will add the most to your simulator enjoyment. Ultimately, it will come down to personal choice. Recreational flight simulation ranges from sitting in a cardboard box pretending to fly¹⁵, to building a detailed replica of the cockpit accurate to the precise color of the Flight Engineer's console. The characteristics that you add to your simulation will depend upon where you are on this continuum and what resources you can bring to bear on your project.

The first step is to understand what you hope to gain by having a recreational flight simulator. If you're looking for the excitement of flying a WWII fighter, modeling rigging cable stretch is far beyond the point of diminishing returns. On the other hand, the means to reflect near-stall control surface buffeting in the stick may be well worth the effort. Based on how you expect to use your simulator, make a prioritized list of the factors/characteristics that will add to your experience.

Research the aircraft you're simulating. This chapter provides an overview of joystick characteristics. If you're simulating a specific aircraft, you'll want specific characteristics. You'll want to know what switches should be on the grip so you can make an informed choice about incorporating them or not.

¹³ Besides the fact that there is another fighter out there flown by a pilot who is not interested in a "win-win" outcome.

¹⁴ These sensors are linear variable differential transformers or LVDTs. They are covered in the Position Sensors chapter.

¹⁵ I'm fairly certain I've outgrown this stage.

Research the simulation software you plan on using for your simulator. Does it offer the means to implement the functionality you want?

Research the rest of your simulator plans, at least in overview. Building a simulator can be a very large project. If you're just starting your simulator project and have already decided on an extreme fidelity joystick, think what this implies for the rest of the simulator. Will it be done to same standards, and do you have the resources to do so? Try to keep the effort demanded of each portion of your simulator in balance.

Control Loading

A control loading system in a simulator mimics the control forces felt by a pilot in a real aircraft. Control loading systems also find application in real aircraft where they supply tactile feedback. In fly-by-wire aircraft, control loading provides the entire control feel. Some aircraft with power assisted controls use loading to reflect flight conditions and to boost pilot situational awareness. Control loading systems may be passive or active.

Passive Control Loading

Springs form the basis of the most common passive control loading systems. They are widely used in game joysticks, find application in some commercial simulators, and even make an appearance in aircraft. Springs are specified by type, dimension, performance factors and material.

The two spring types you're most likely to use in control loading are the extension spring and the compression spring. An extension spring gets longer when the ends are pulled. A compression spring acts just the opposite. It gets shorter as the ends are pushed together.

The general dimensions used to specify a spring are the length inside the end loops for an extension spring, the free length (i.e. non-compressed length) of a compression spring, the outside diameter, and the diameter of the wire making up the spring. When you look a bit closer, typically by looking at a spec sheet rather than a catalog listing, you'll see several other dimensions called out. The body length of an extension spring is useful to know as the dimensions of the end loops can vary widely.

A key performance factor is the spring rate¹⁶. This is the "springiness" or "stiffness" of the spring. It's the force required to change the spring length by a certain amount. For example, a compression spring with a spring rate of 2 pounds/inch will become 1 inch shorter when squeezed by 2 pounds.

An extension spring also has a spring rate; however, there is an additional factor to keep in mind. An extension spring is manufactured with an internal tension to keep the coils tightly together when there is no external force applied to the spring loops. This is referred to as initial tension. An extension spring with a spring rate of 2 pounds/inch and

¹⁶ Also known as the spring constant.

an internal tension of 1 pound will require 3 pounds force to extend the spring the first inch. One pound is needed to overcome the initial tension. The remaining 2 pounds extend the spring. Once the coils are pulled apart, the spring rate acts the same in an extension spring as in a compression spring (though in a different direction). Continuing the example, if the force is increased from 3 pounds to 5 pounds, the spring will extend an additional inch.

Spring rate is a useful linear approximation to spring behavior, because spring length does, in fact, change in proportion to the changes in force. But, this is true only to a point. If you apply enough force to a compression spring, the coils will touch, and it stops behaving like a spring. Apply enough force to an extension spring and it's stretched out of shape. So, a final performance factor to keep in mind is the maximum load specification. This is the largest force you can apply to a spring without damage.

Steel music wire, and stainless steel wire are the most common spring materials. Stainless is slightly more expensive, but is corrosion resistant. Either will work in simulator control loading applications.

Springs are available through large hardware stores and building supply centers. Vastly larger selections can be had through industrial suppliers like MSC Industrial Supply Co., and McMaster-Carr.

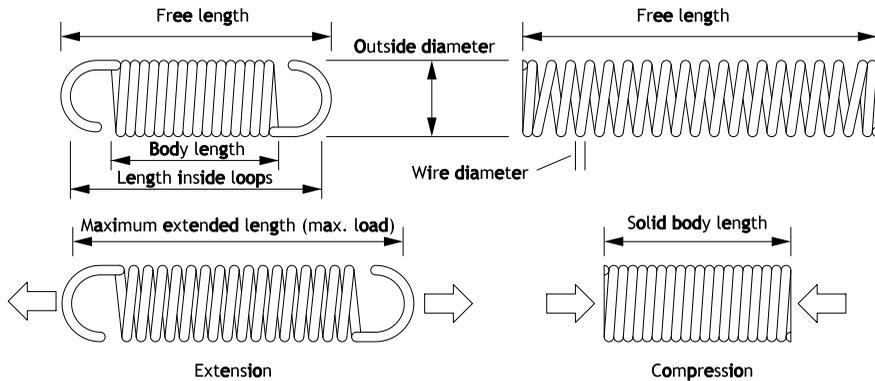


Figure 4. Extension and compression springs.

Through appropriate use of cams and linkages, a spring based control loader can provide control forces that vary in proportion to control movement, or vary in some nonlinear fashion, perhaps, for example, becoming stronger with extreme control movements. This can nicely model aerodynamically induced control forces over a limited, but useful, range of flight conditions, (for example, level flight over a restricted range of airspeeds).

Unfortunately, this is not what you'll find in most consumer game joysticks. In these units the springs simply provide a centering force for a bit of tactile feedback. A further shortcoming is the presence of a centering detent, much to the detriment of realism¹⁷.

Nonetheless, if you're building your own flight controls, a spring based control loader can be an acceptable choice. The control loader forces can be tweaked to approximate true stick forces over a limited range of flight conditions for non power assisted controls. For a fly-by-wire simulation, this may be the preferred approach. In both cases springs have the advantages of simplicity and low cost.

Hydraulic damping can boost realism. It adds a solid feeling to the controls that suggests that you're operating control surfaces with real mass, through an array of linkages rather than simply pushing on springs located a few inches away. Small hydraulic dampers¹⁸ are readily available, inexpensive additions. (See the Pedals chapter for a project utilizing hydraulic dampers for control feel.)

A hydraulic damper is a sealed cylindrical device with a movable piston. The body of the damper contains hydraulic fluid and pressurized dry nitrogen gas. As the shaft moves the piston, the hydraulic fluid is forced through a small orifice in the piston. If the piston is moved slowly, the force required is relatively low. Moving the piston rapidly requires much more force. This is the basic nature of a damper, a force that opposes motion of the piston, and which increases as the speed of that motion increases.

A damper may generate a damping force on extension, compression or both. The damper in the illustration does so in both directions. Some damper models incorporate a one-way valve in the piston which by-passes the orifice. When the piston moves one way, the valve disk blocks the by-pass and the fluid is forced through the orifice. Normal damping occurs. Moving the other direction displaces the disk and the fluid can pass through the larger valve opening. Damping is much reduced.

Gas springs are similar to hydraulic dampers. The primary difference is that gas springs are filled mostly with pressured nitrogen. They contain a small amount of hydraulic fluid to lubricate the seals and provide damping at the shaft extension limit. Gas springs produce a nearly constant force throughout the shaft stroke. Containing the pressurized nitrogen requires that the shaft seals be very tight. As a result the seals contribute substantial frictional forces. The rule of thumb is that the shaft friction equals 9% of the rated spring force. Gas springs have found limited use in control loading. You'll have more design flexibility if you use separate steel springs and hydraulic dampers.

¹⁷ I find this extremely annoying. As a private pilot I've had the controls of several types of aircraft, including a helicopter. None has had control detents. Don't these companies understand that recreational flight simulation isn't a game? This is serious business!

¹⁸ Hydraulic dampers like those made by H. A. Guden Co. (www.guden.com) are good choices. They are sold through industrial supply vendors like MSC Industrial Supply Co. (www.mscdirect.com)

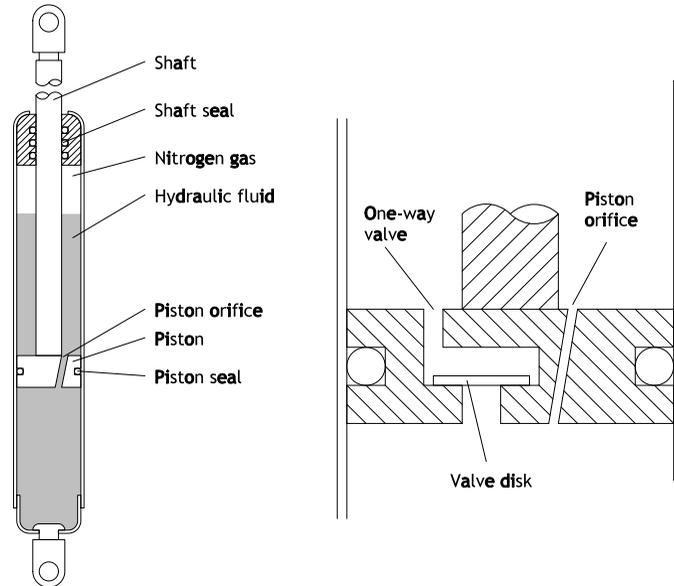


Figure 5. Hydraulic damper.

Don't forget basic friction in control loading. While most aircraft are designed to minimize friction in the control linkages (who wants binding controls, after all), some aircraft like Bell helicopters, have adjustable friction controls on the collective and cyclic. Adding a similar friction mechanism to your helicopter sim can boost its realism. The project in the Engine Controls chapter demonstrates the use of adjustable friction.

A spring based control loader is a good choice for a force activated joystick like the Falcon F-16 SSC. The spring should be quite stiff and the grip deflection limited to a fraction of an inch to accurately reproduce what the pilot feels in flight.

A hydraulically damped, spring based control loader works well for simulating movement activated controls of fly-by-wire aircraft like the Airbus series, since this is exactly what the pilot feels in the actual aircraft.

Active Control Loading

Some commercial simulators use active control loading systems to apply forces to the flight controls. Contemporary active control loaders utilize electric motors. Older control loaders were based on hydraulics. Active control loading systems are capable of reproducing flight control forces with great fidelity.

The next figure shows the basics of active control loading. The heart of the system is a computerized motor controller. It calculates the force that should be felt by the pilot based on parameters such as airspeed and altitude supplied by the flight simulation

application, and on the current position of the stick as reported by the stick position sensor. The controller then compares the calculated force with the actual force as measured by a force sensor in a linkage that connects the motor gear box lever arm to the stick. If the measured force is too small, the controller increases the power to the motor. If the force is too large, motor power is decreased.

The motors used in control loading are designed to operate at low speed or in a stalled condition. You may see these motors referred to as “torque motors” or “servo motors”. (The more commonplace motors used in fans and power tools tend to overheat if used in this application.) The motors generally drive a gear box to multiply the delivered torque.

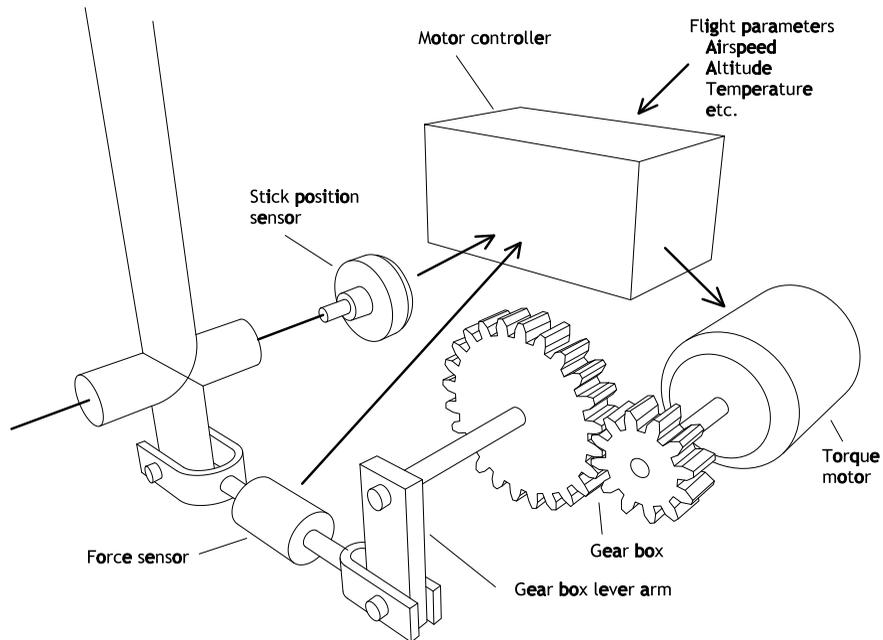


Figure 6. Active control loading basics for a single axis.

Active control loading systems are used in some aircraft as well as in simulators. The simplest is the “stick shaker” which vibrates the control column to warn of an approaching stall. Some Boeing airliners incorporate “feel computers” that vary the yoke and rudder forces felt by the pilots to provide additional cues about the aircraft flight condition¹⁹.

¹⁹ This is an interesting difference in design philosophy between Boeing and Airbus. Boeing has added systems to produce control feel representative of control surface aerodynamic forces. Airbus has chosen to completely isolate the pilot from those forces.

A simulator stick shaker can be made using a small motor coupled to an off center weight. A more sophisticated approach is to use a bass shaker²⁰. A bass shaker is a “tactile transducer” used to inject low frequency sound into things, usually seats, so that the vibrations are felt rather than heard. While the bass shaker is usually driven from an audio system, there is certainly no reason not to take a more creative approach. A micro controller could generate a selection of waveforms to simulate buffeting from an impending stall, the thump of weapons release, or the rhythmic vibration induced by the helicopter rotor. Alternatively, one might use a dedicated sound card with specially developed sound files.

There has been sporadic experimentation with “quasi-active” control loading within the hobby community. The most common approaches have been to start with passive control loading and use a motorized lead screw to adjust the leverage of the loading. For example, one promising approach used a pendulum for control loading²¹. A lead screw adjusted the position of the pendulum weight relative to the pendulum pivot point. The closer the weight is to the pivot, the easier it is to move and the lower the control forces are. A shortcoming of this approach is that motor driving the lead screw was noisy and shook the controls. It was otherwise effective.

A hobby built active control loading system similar to commercial systems is not out of the question. It would be an advanced project, but suitable materials are available.

Purchase Options²²

The joystick is a very common game controller for PC based applications. Doing a web search on “joysticks” will produce a vast array of options. Searching the online auction sites will produce more. Here are a few of the high-end offerings that you should be careful not to miss.

Itra GmbH makes pilot and F/O Airbus SSC grips that can be used on other manufacturer’s game joysticks. (sim.itra.de)

Tarmac Aces markets a small but growing selection of highly accurate historical aircraft controls for simulators. (www.valiant-studio.eu/tarmac/html/en/hangar.php)

Flight Deck Solutions sells raw molded Airbus SSC grips. You finish them yourself. There is a tutorial on the FDS site. (www.flightdecksolutions.com)

²⁰ Sold by Aura, Guitammer (the ButtKicker® guys), Clark Synthesis, etc.

²¹ I believe this idea was original posted to an Avsim forum by “Tigert”.

²² Caveat: I am not endorsing these products. They are listed here to give you an idea of what the market offers as you deliberate make-versus-buy decisions in pursuit of your ultimate home flight simulator.

The ThrustMaster Cougar HOTAS is perhaps the best F-16 style game controller. Although I repeat my caveat about not endorsing any particular product, the Cougar user community is quite vocal in their enthusiasm. I suspect there is a reason for it. The Cougar has been subject to several user modding efforts. One replaces the standard potentiometers with rotary hall sensors (www.cubpilotshangar.net), while a second converts the SSC to a force activated control (www.eaglevision.nu/fcc.php and www.realsimulator.com/html/fssb.html). There have been several (short-run and now apparently discontinued) modifications that replaced the stock gimbals with heavier, more tightly machined ones. (www.thrustmaster.com)

Flight Link Aviation Training Devices makes the G-Stick III, a floor mounted cyclic. Actually, Flight Link makes a complete R-22 helicopter flight simulator. (www.flightlink.com)

Logitech sells joystick game controllers including the high-end Flight System G940. (www.logitech.com)

MRVC (Multi-Role Virtual Controls) helicopter controls are available from SimControl. MRVC controls are used as professional training aids. (www.simcontrol.co.uk)

Heli-Kit is a collective stick that is USB interfaced. (www.heli-kit.com.ar)

CH Products has a commercial division (separate from the gaming division) that makes heavy duty joysticks that might be of interest for your projects. (www.chproducts.com)

Infinity Aerospace markets a military style flight grip (similar to a cobra grip) to the experimental aircraft crowd. This is one of the few sources for left-hand flight grips. It's also a source of 4-way hat switches. (www.infinityaerospace.com)

MaxFlightStick makes fixed-wing and rotary-wing flight controls for simulators. (www.maxflightstick.com)

The Ray Allen Company makes flight rated stick grips that are widely used by the experimental aviation crowd. (www.rayallencompany.com)

Suzo-Happ Group manufactures components and systems used in arcade gaming. They supply replacement parts that may be of interest to the DIY sim builder. (www.happ.com)

Aircraft Spruce & Specialty Co. sells the expensive and very high quality B-8 and Cobra flight grips made by Otto Engineering for those with an insatiable desire for real aerospace gear. Spruce also sells a more affordable version of the B-8 grip cast from ABS plastic. (www.aircraftspruce.com)

The Aviation Simulation Group offers various simulated items including f-16 and F-18 flight grips. (www.aviationsimulationgroup.com)

Perhaps the lowest cost option for a military style grip is buying a used joystick on an online auction site like Ebay. Thrustmaster modeled some of its products on the B-8 grip. Suncom Technologies modeled the F-15E Hawk and Talon joysticks on the grip used in the F-15 and F-18. (Note that while the castle and hat switches on the Talon model are functional, on the lower cost Hawk model these two switches are non-functional cosmetic moldings.)

Further Information

Many older military technical manuals have fallen into the public domain. Maintenance manuals can be of particular value to the flight simulation hobbyist interested in building highly realistic simulators. Detailed drawings of flight controls and linkages are an integral part of inspection procedure descriptions covered in these manuals. Even if you're not interested in military aircraft, some commercial models were developed from their military cousins. For example, the OH-58 Kiowa became the 206B Jet Ranger. Several companies collect these manuals and publish them in electronic form: eFlight Manuals (www.eflightmanuals.com), Flight Manuals on CD (www.flight-manuals-on-cd.com) Integrated Publishing (www.tpub.com), Military Manuals (www.military-manuals.com), and Military Media Inc. (www.military-media.com/military).

Training manuals for A&P maintenance classes contain a wealth of information about flight controls. For example, check [Aircraft Maintenance and Repair](#) by Bent and McKinley.

Driven Technologies, Inc. makes joysticks for F-22 and F-35 military simulators. You may find the on line product literature helpful. (www.driven-technologies.com)

Mason Controls makes control, flight, and throttle grips used in U.S. military aircraft. It's unlikely that you'll be interested in buying from these guys unless you have an outstanding excess of cash. However, Mason is an excellent source of information in the form of its online catalog which is full of dimensioned engineering drawings. (www.mason-electric.com)

Otto Engineering is another manufacturer of military and aerospace grips including helicopter flight grips. Prices are high. The Otto Engineering web site offers mechanical drawings of various aerospace control grips in its product literature. (www.ottoeng.com)

Essex Manufacturing makes various military flight grips. However, Essex will not sell to the general public. Once again, this is presented as a source of information. (www.essexind.com)

Hi-Rev Simulations makes a variety of very realistic flight and throttle grips. HRS does not sell to the casual hobbyist, but does have a variety of interesting pictures on its web site. These may be useful if you choose to pursue a DIY grip. (www.hirevsims.com)

Guardian Electric Manufacturing Co. manufactures a variety of flight and motion control grips. Guardian does not sell to the general public, but the company site does provide basic documentation in the product literature section, perhaps useful if you're building your own grip. (www.guardian-electric.com)

FAST magazine is a publication of Airbus Industries covering various technical topics relating to the Airbus fleet. For information about the Airbus sidestick controller see: "Flight Control System", FAST no. 5, "Airbus Fly-By-Wire Aircraft at a Glance", FAST no. 20, "Mini Sidestick Controller", FAST no. 3, and "Advanced Technology and the Pilot", FAST no. 14. (www.content.airbusworld.com/SITES/Customer_services/html/fast14.htm)

Flight Simulation, ed. By J. M. Rolfe and K. J. Staples provides a somewhat dated, but still informative, technical overview of control loading.

Project: Joystick

Projects can provide great satisfaction and enjoyment. It can be very satisfying to personally create something that is too expensive to buy, or just plain not available. The completed projects can enrich the simulator illusion, and add to the overall enjoyment of the hobby.

Projects also provide a means to demonstrate different construction techniques. Since flight simulation can grow into a terrifyingly expensive hobby, being able to make high-quality simulator components from inexpensive, easily located materials is a good thing. So this book presents projects based on various approaches and using an assortment of materials to help you build a "toolbox" of techniques that you can apply to projects of your own design.

This particular project is a floor mounted joystick. The majority of the materials are inexpensive home construction supplies: wood, door hinges, electrical conduit and the like. For the flight grip, we'll take a shortcut and use the grip from a salvaged game joystick. We'll use a pair of inexpensive magnetic-field Hall sensors and a few ceramic craft magnets to generate a pair of voltage outputs for reporting the joystick pitch and roll positions to the simulation computer.

The bulk of the joystick mechanism is designed to mount under the simulator cabin floor with the joystick control tube extending upward through a rectangular cutout. The prototype version described here is actually built into a standalone box so that there are places to fasten the optional control loading springs. Ideally, you'll incorporate the

mechanism into the sub-floor structure of your simulator, adding suitable mounting points for any desired springs.

The control tube is made from 1" diameter, thin wall electrical conduit (referred to as "EMT" in the building trades). This is fairly bulky stuff, chosen not for its strength, but because it projects a massiveness that fits the desired flight illusion. To avoid having to bend this conduit, we'll use a standard, preformed 90 degree conduit section. We'll use standard fittings to connect the curved section to the straight piece, and to connect the salvaged joystick grip to the curved section.

The joystick pivots in the roll direction around a quarter inch bolt. It pivots pitch-wise on a pair of standard door hinges that serve also to mount the mechanism to the bottom of the simulator floor. Movement of the joystick rotates magnetic fields around a pair of Hall sensors. This changes the sensor voltage outputs which are in turn reported to the computer interface.

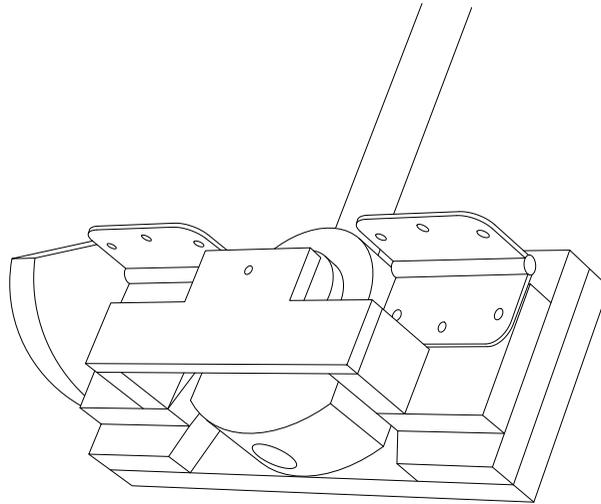


Figure 7. Joystick sub-floor mechanism.

The stick base consists of a length of straight 1" thin wall electrical conduit glued to a laminated wood roll pivot. The roll pivot is built up from three layers of 3/8" plywood and one layer of 3/4" clear pine. Urethane glue holds the wood pieces of the prototype together, but any good wood glue should do the trick.

The length of the conduit depends upon how you mount the joystick pivot mechanism and the height of the seat you'll be using. The length called out for this project is based on mounting the pivot in a stand-alone box set on the floor and using a seat with a seat cushion top 13 inches above the floor. If you mount the stick mechanism beneath the simulator floor you'll want to start with at least 14" of conduit. If you're uncertain what length to use, start with several extra inches so you can trim to fit.

Glue the bottom three layers of the roll pivot together first without adding the top layer. Once the glue has cured, dried or otherwise solidified, we can fit the conduit. You'll probably notice that the conduit is slightly larger in diameter than the depth of the slot in the roll pivot. If you have a large vise, you can slightly flatten the end of the conduit to fit the slot. Alternatively, you can use the end of the conduit as a gouge to scrap a shallow groove into the bottom of the slot. In either case, the conduit should fit within the slot so that the top piece of plywood makes good contact with both sides of the roll pivot.

The conduit will be seated in a bed of polyester filler. You can use either automotive filler or general purpose wood filler. Just make sure it's the type you mix the hardener with. The water based fillers won't work. Use sandpaper to roughen the portion of the conduit that will sit in the roll pivot slot. This will greatly strengthen the bond of the filler to the conduit. Make sure there no saw dust remains in the slot. Mix the polyester filler according to the directions on the can. Use a small putty knife to put most of the filler into the slot. Force the filler into the wood grain then fill the corners of the slot. Place the conduit in the slot with the end about ¼" away from the curved end of the roll pivot. Add more filler up to the top of the slot. Use a small clamp to hold the conduit in position while the filler cures.

The polyester filler will progressively harden over fifteen to thirty minutes. Once it has become moderately firm, but not rock solid, it's possible to trim the filler with a knife or wood chisel. You'll have a period of several minutes during which it's easy to remove any excess. You can trim it later, of course, but it's then more like sanding or carving hardwood.

If there are any voids, fill these with more polyester filler. Allow this to cure then sand the top smooth. Using wood glue, bond the top plywood layer in place. Make sure the pilot holes in the plywood do not become blocked with glue. Once the glue has dried, remove any excess and sand the edges.

Drill the hole for the pivot bolt. It's important that this hole be perpendicular to the plywood. Ideally you should drill this on a drill press. Countersink the hole with a 1" diameter spade or Forstner bit. Make this as deep as you can without chewing into the conduit. Depending on the specifics of your drill bit, this will be about 5/8". This will recess the head of the pivot bolt, keeping it from distorting the magnetic field for the Hall sensor.

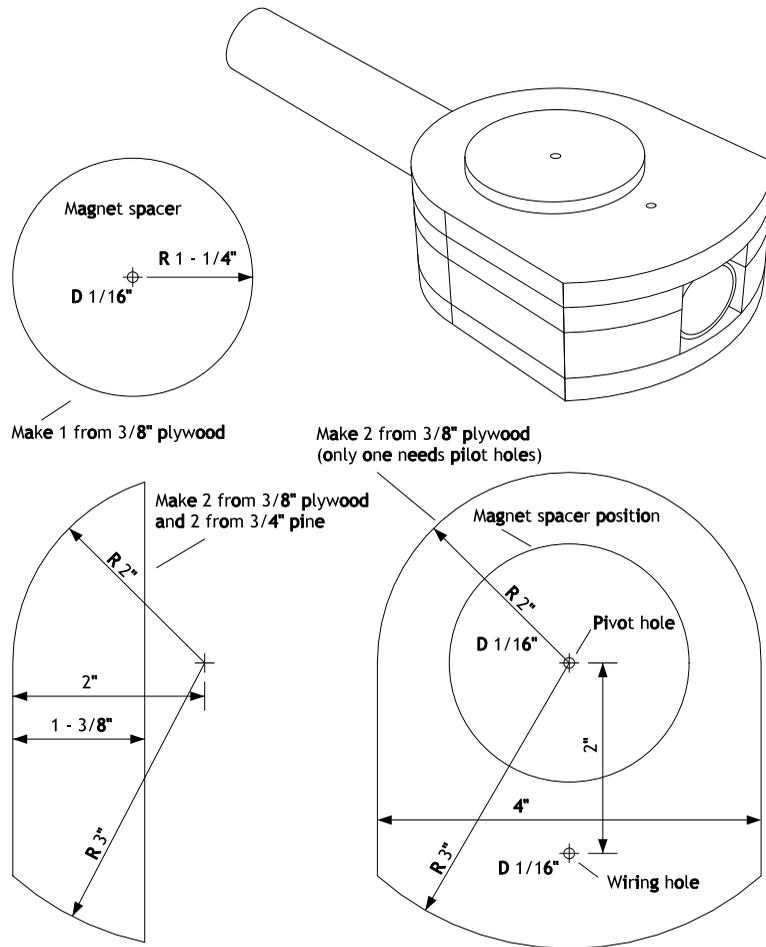


Figure 8. Roll pivot parts and assembly.

Drill the rest of the way through the pivot hole to a finished hole diameter of $\frac{1}{4}$ ". You will get best results by enlarging the pilot hole in steps by using a sequence of increasingly larger drill bits. This will reduce the chance of the drill bit drifting from its intended position, result in a more nearly round hole, and minimize the development of burrs on the hole edges.

Drill a second hole for running wires up the joystick shaft to the stick grip switches. This hole need only go through the top plywood layer and into the conduit. It's convenient to have a finished diameter of $\frac{1}{2}$ ", but a hole as small as $\frac{1}{4}$ " is workable.

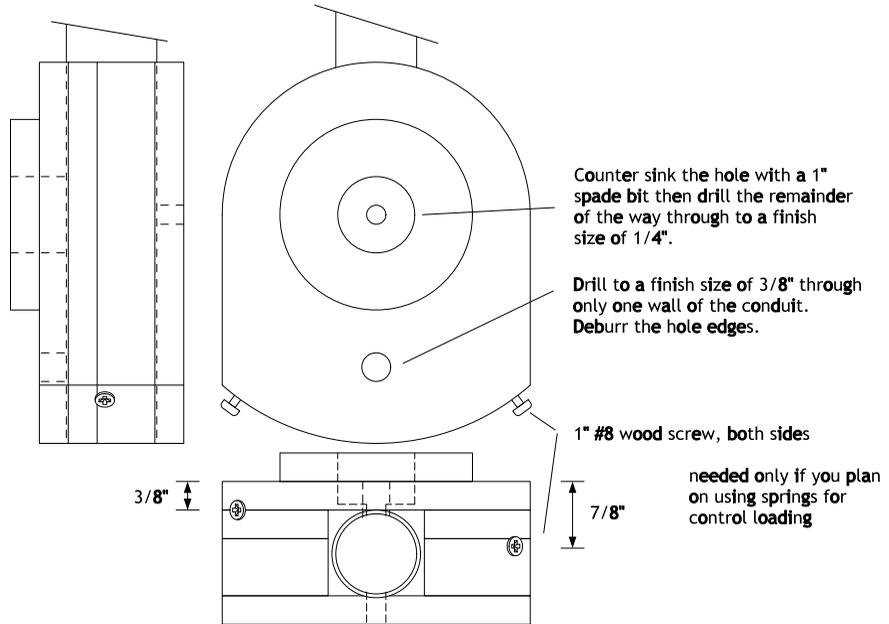


Figure 9. Roll pivot details: holes and screws.

Clean up the edges of the holes. The inner edge of the wiring hole is the one to be most concerned about. If this is sharp or ragged, joystick movement will eventually cause those edges to cut through the wire insulation.

The final steps are to add screws where the control loading springs will attach. Leave about 1/8" of each screw shaft exposed. If you don't plan on using control loading, you don't need these screws.

Construction of the pitch assembly starts with cutting and gluing seven pieces of 3/4" pine as shown in the following figure.

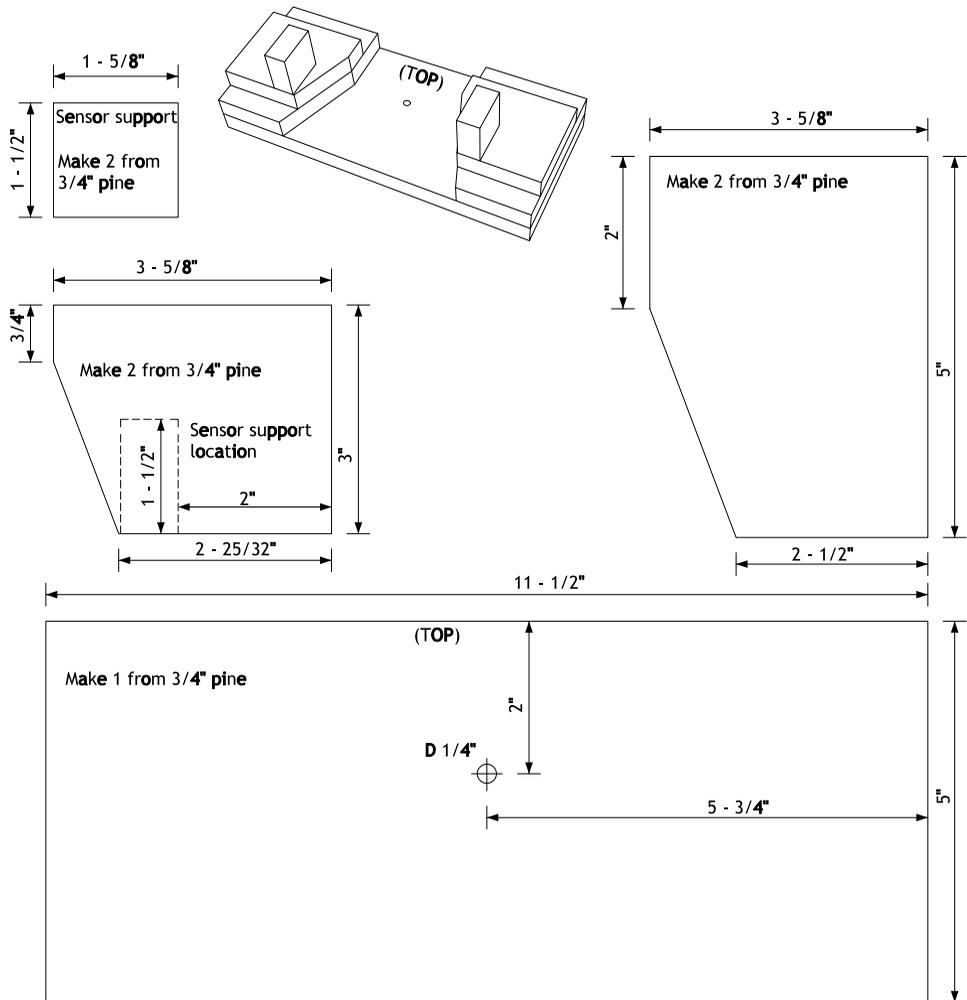


Figure 10. Pitch assembly basic parts.

The pitch assembly will eventually be mounted underneath the top of the joystick base (or the floor of your simulator cabin) using a pair of hinges and $3/4"$ spacer. The spacer provides clearance so the hinges will move smoothly. To mark the hinge mounting holes on the pitch assembly, you'll need to use a piece of $3/4"$ material to properly position the hinges against the assembly. Mark the hinge mounting holes as shown below.

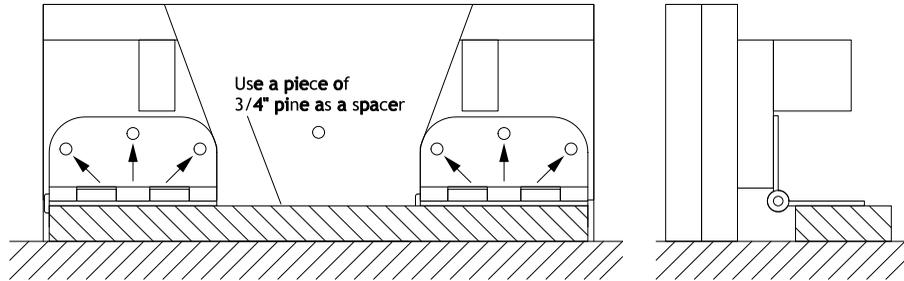


Figure 11. Position the hinges and mark the hinge mounting holes.

We'll be fastening the hinges to the assembly using $\frac{1}{4}$ " bolts. No wimpy wood screws for us! Bolts provide a bit of latitude in aligning the hinges as the holes in the hinges are slightly larger than the bolt diameter. Using bolts also means it's possible to disassemble the project for the inevitable tweaks, mods, and upgrades²³ without worrying about stripping out the holes.

Drill the hinge mounting holes in the pitch assembly. This is best done using a drill press²⁴ as the holes should be perpendicular to the wood surface. As with the holes in the roll pivot, start with a small diameter pilot hole ($\frac{1}{16}$ " or so) and work up to $\frac{1}{4}$ " in small steps. These holes go all the way through the body of the assembly.

The joystick pivots around a $\frac{1}{4}$ " bolt when moved side-to-side. The bolt should be tight enough to hold the joystick components together, but not so tight that the joystick is hard to move. Because we're using wood, we need to accommodate dimensional changes due to moisture variation. This is a good application for a compression spring²⁵.

We can make an elastomeric²⁶ spring using a standard flat washer and a bit of silicone bathtub caulking. Wrap masking tape around the outside edge of a 1" flat washer to form a $\frac{1}{4}$ " lip. Wrap a strip of plastic wrap around the shaft of a $\frac{1}{4}$ " bolt and place the bolt through the washer as shown. Place a $\frac{1}{4}$ " layer of silicone kitchen and bathroom sealant on the washer. It's important that it be a silicon-based sealant. The latex-based sealants

²³ Flight simulation is a very hands-on hobby practiced by very creative people. I have no expectations that any of the designs presented in this book can't be improved, or that no one will see fit to modify them. In fact, I look forward to seeing what people come up with. Please post pictures of your projects on your website or on a flight sim forum.

²⁴ A drill press is a very useful tool. It can be a small, inexpensive model. Many of the projects in this book were made using an import benchtop drill press that cost about \$120.

²⁵ Bellevue disc springs could be used in this application. However, as this project is meant to demonstrate what can be made with more commonly found materials, we'll stick with the DIY elastomeric compression spring. If you find Bellevue disc springs more appealing, they are available from industrial suppliers like MSC Industrial Supply Co.

²⁶ I just love using high-tech words. "Elastomeric". Woohoo, almost sounds like I know what I'm talking about.

simply don't have the needed springiness. Once the sealant has cured remove the tape, bolt, and as much plastic wrap as will tear free.



Figure 12. How to make an elastomeric compression washer.

While the elastomeric washer is curing, we can make the pitch motion stop block from $\frac{3}{4}$ " pine as shown below.

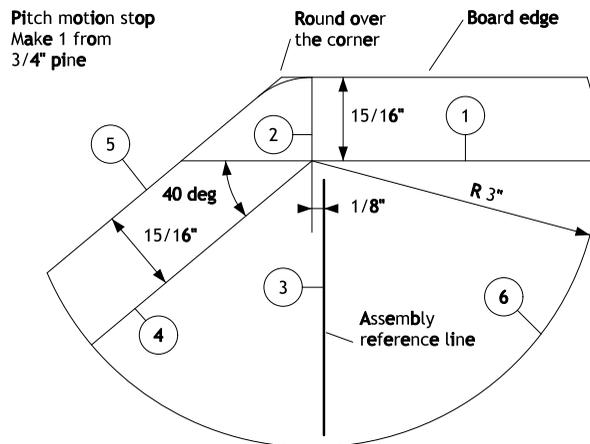


Figure 13. Pitch motion stop and spring cam.

The motion stop has an odd shape because it doubles as the cam for a pair of optional control loading springs. Lay out the markings directly on the wood using a square, a rule, a compass, and a protractor.

Draw a line (1) parallel to and $\frac{15}{16}$ " in from the board edge. Draw a second line (2) perpendicular to the edge at least three inches from the right end of the board. Draw a line (3) parallel to and $\frac{1}{8}$ " to the right of line #2. Line #3 will be use to position the motion stop when we fasten it to the pitch assembly. Draw a line (4) from the intersection of lines #1 and #2, at a 40 degree angle from line #1. Draw a line (5) parallel to and $\frac{15}{16}$ " from line #4. Draw a 3" radius arc with the intersection of lines #1 and #2

as center. Cut along line #5 and the arc. Round over the corner where line #5 and the board edge meet.

Drill a small (1/16" or so) hole through the stop at the intersection of lines #1 and #2. We'll use this later to position the magnets used with the Hall sensor.

Glue the motion stop to the pitch assembly as shown below. Nails or screws aren't necessary, though there is no reason not to use them as long as you're careful to avoid the hinge mounting holes.

Draw a line on the end surface of the pitch motion stop from the upper edge to the small hole. Use a square so that the line is perpendicular to the edge. We'll use this line to properly position the pitch assembly when installing the hinges.

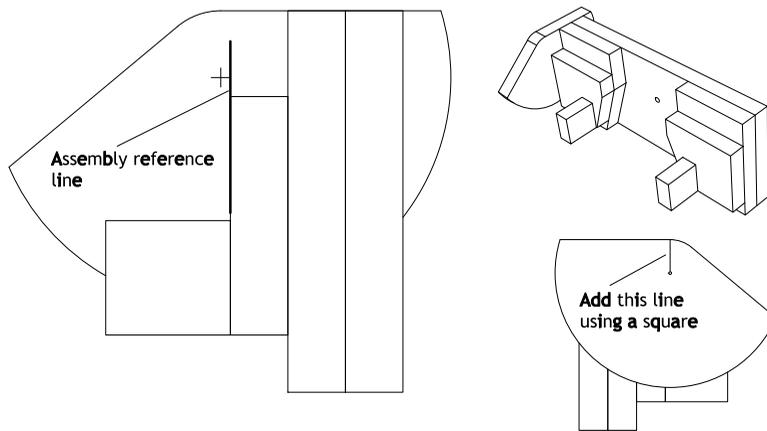


Figure 14. Installing the pitch motion stop.

At this point, we have enough completed to mark the hinge mounting holes on the joystick box. It's better to do it before we install anything else on the pitch assembly. Unfortunately, we haven't built the box yet, so put the pitch assembly aside while we do.

Start with the box top. The rectangular cutout provides clearance for the joystick shaft. The rounded corners are not strictly necessary. They just look nice. You can make the curved layout lines by tracing around the end of a piece of 1" conduit or a coin of a similar size. The hinge reference and motion stop position lines will be used to properly locate the pitch assembly when we mark the hinge mounting hole positions.

The hinge spacers will be held by the hinge mounting bolts, but gluing the spacers in place first will make marking and drilling the mounting holes easier. If the spacers are improperly positioned they can interfere with the motion stop or result in misalignment

of the Hall sensor magnet assembly. It's a good idea to mark the locations of the spacers on the plywood so you can see if the spacers shift while you're gluing them in place.

Once the glue holding the spacers has set up, we can mark the hinge mounting hole locations. Install the hinges on the pitch assembly then place the assembly on the lower surface of the top. The centers of the hinge pins should be directly above the hinge reference line. The outer edge of the pitch motion stop should be aligned with the motion stop position line, and the line from the small hole in the motion stop should line up with the hinge reference line. Mark the hinge mounting holes on the spacers.

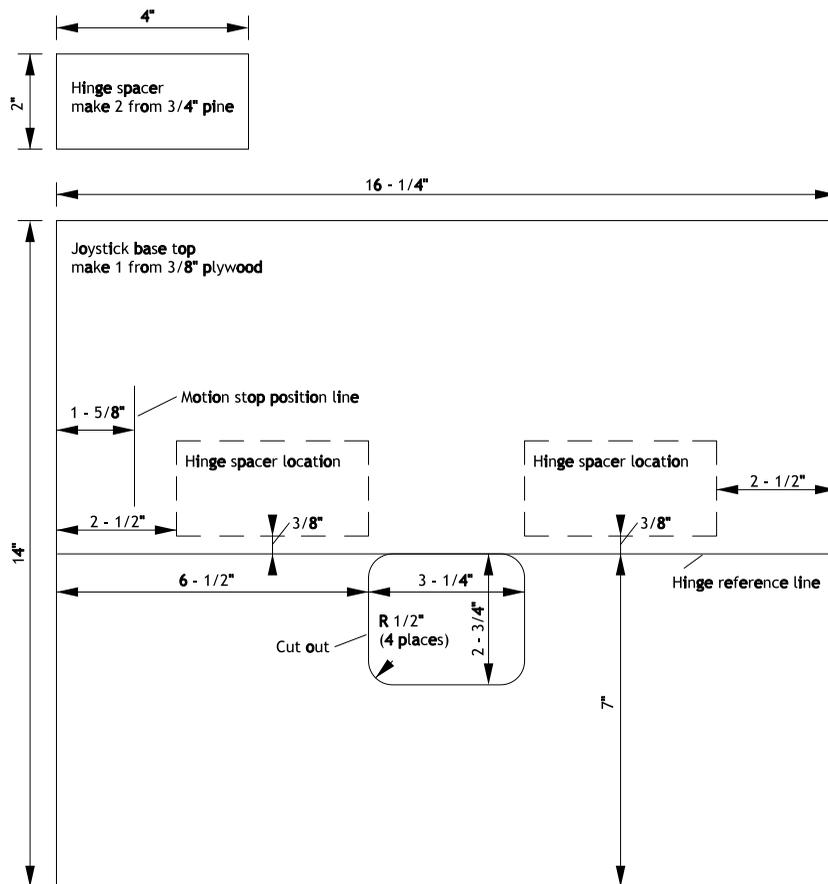


Figure 15. Joystick base top and hinge spacer.

Drill 1/4" diameter holes at those locations. Flip the top over and countersink the holes for flat-head 1/4" machine screws then set the top aside.

One of the box sides will hold the pitch motion Hall sensor in a $7/32$ " hole. The sensor will be inserted into the hole from the outside of the box. This will leave the wires from the sensor exiting the box in an inconvenient place, so there is a second hole to stuff the wires back inside the box. Both of these holes should be recessed so that the wires are protected. Use a 1" diameter Forstner or spade bit to cut a $3/8$ " deep recess. Cut a small channel between the two recesses.

When you're marking the hole locations, also add a reference line from the sensor mounting hole to the board edge using a square. When you assemble the box, align this mark with the hinge reference line on the box top. Fasten the remaining sides to the top as shown in the next figure.

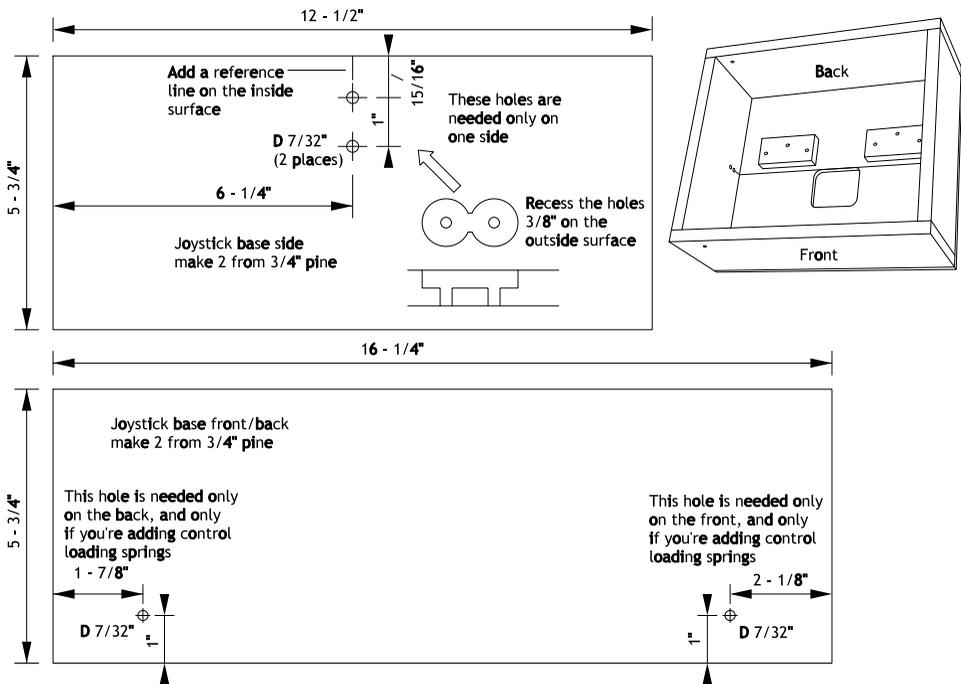


Figure 16. Joystick base sides.

If you use nails in assembling the box, make sure to countersink them. Once the glue has cured, round over the corners and edges on the box as they will be at ankle level when you use the joystick. A $3/4$ " radius works well.

If you plan on adding control loading springs, now is the time to add the attachment brackets for the roll motion springs to the pitch assembly. If you're planning on using this project as a helicopter cyclic you may choose to go without control loading and can skip this step.

The attachment brackets are small rectangular pieces of steel plate with a few holes in them. The material isn't particularly important as long as the bracket is stiff enough. In keeping with the buy-it-at-the-home-building-supply-center sub-theme of the chapter, I bought a couple of 4" steel corner brackets, and cut one up to make the spring mounts.

Hole positions are not particularly critical. Judicious cutting around the existing holes will provide you with one of the holes leaving only two per bracket to drill. Fasten a spring bracket to each end of the pitch assembly using 1" #8 flat-head wood screws. Pilot holes for the screws will make installation a bit easier.

We also need to add a pair of wood screws to the curved side of the pitch motion stop. These are the attachment points for the pitch motion control loading springs. Drill generous pilot holes for these screws.

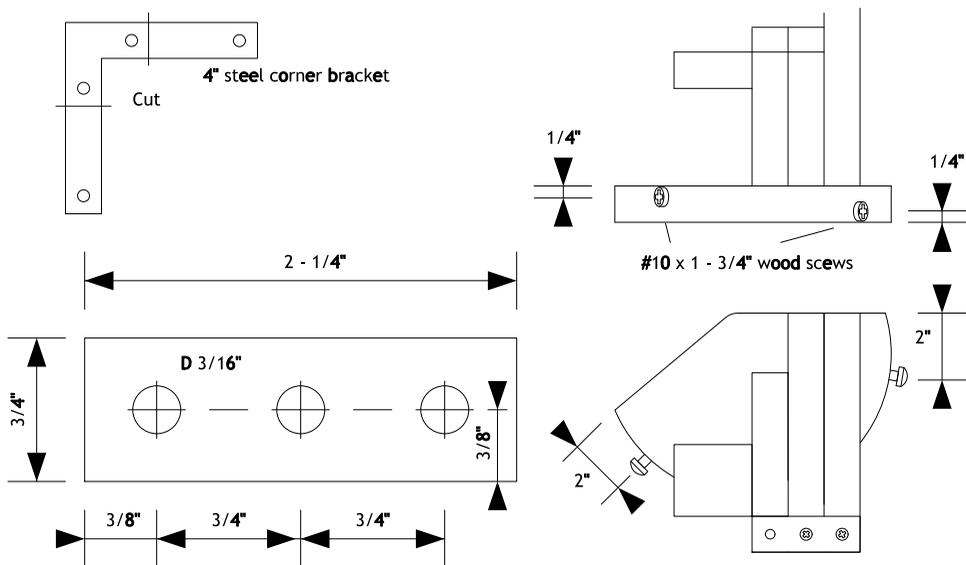


Figure 17. Pitch assembly spring attachment points.

We'll need two magnet assemblies. Each assembly holds a pair of 3/4" diameter ceramic magnets. The assembly bodies are 3/4" lengths of the same 1" electrical conduit we're using for the joystick shaft. Each magnet sits on a "shelf" made from mild steel plate. A good source of this plate is a 4" steel corner bracket like the one used for the spring mounting brackets.

The shelves should have beveled edges where they contact the inside of the conduit. The shelves and the conduit form the magnetic back circuit. We're primarily interested in the magnetic flux in the gap between the two magnetic. But if you get flux from one

face of a magnet, you must contend with the returning flux to the other face. The back circuit contains that returning flux, both strengthening the flux in the gap, and reducing extraneous flux outside the conduit. By beveling the edges, you create a better magnetic joint between the shelves and the conduit.

Trial fit the pieces as you bevel them. Aim for a $5/16$ " gap between the magnets. Glue the shelves in place using fast set epoxy.

The mounting tabs for the magnet assemblies are not critical. I cut the tabs from a galvanized mending plate from a lumber store. Exact hole placement or dimensions aren't important.

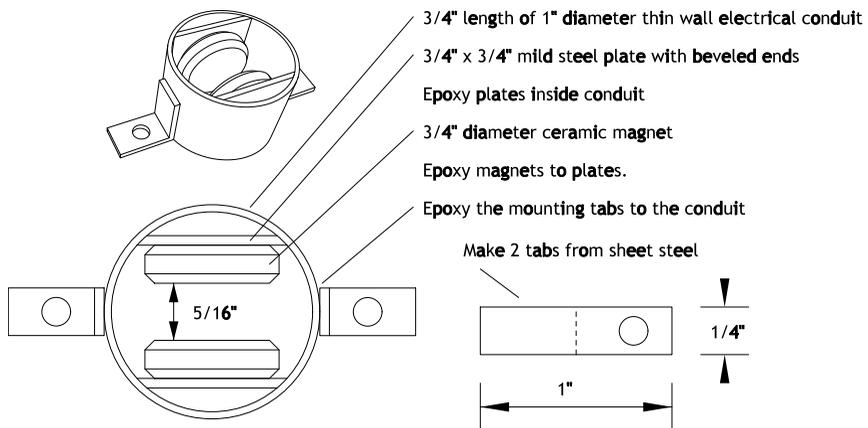


Figure 18. Hall sensor magnet assembly.

Fasten one of the magnet assemblies onto the pitch motion stop as shown below. The magnet gap should be centered on the pilot hole in the stop. The angle isn't critical as we'll adjust for that when setting up the Hall sensor.

The second magnet assembly goes on the roll pivot. Position the magnet assembly as shown below. The magnet gap should be centered on the pivot hole. Mark the locations of the mounting holes and set the magnet assembly aside. Drill pilot holes for the holes.

Mount the roll pivot to the pitch assembly using a $3 - \frac{1}{2}$ " by $\frac{1}{4}$ " bolt, washers, and two nuts. Use a flat steel washer underneath the bolt head. Use the elastomeric compression washer, a steel flat washer, and a brass flat washer underneath the nuts. Tighten the first nut to compress the elastomeric washer slightly. The roll pivot should be held firmly against the pitch assembly, though not so tightly that it becomes difficult to move. Use the second nut to lock the nuts in place on the bolt threads. A single nut would quickly be loosened by joystick movement.

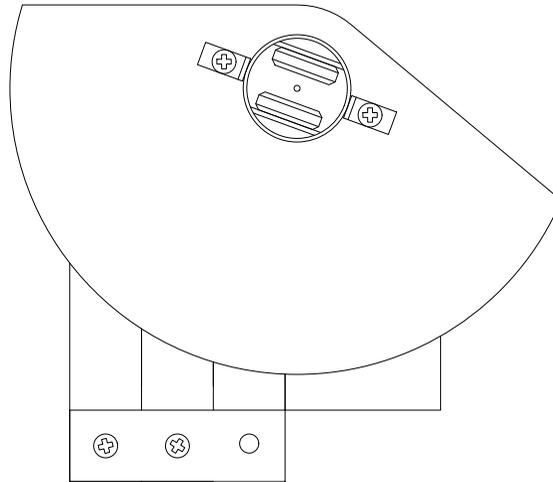


Figure 19. Fastening the magnet assembly to the pitch assembly.

Fasten the magnet assembly to the roll pivot with two 1/2" #6 wood screws.

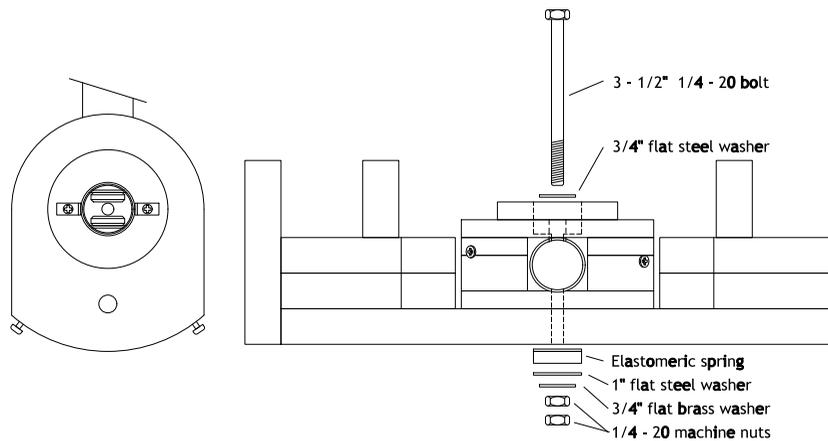


Figure 20. Installing the magnet assembly on the roll pivot.

We will mount each Hall sensor inside a short length of brass tube to protect it, and to rigidly hold it in position in the magnet gap. The first step is to glue a brass flat washer to one end of the brass tube. A #10 washer works well though you will have to enlarge the hole slightly. The washer provides the means to lock the tube in position with another washer and a wood screw.

Solder 24" extension wires to each of the three leads on the Hall sensor, taking care to insulate the leads and solder joints. Use different colors for each wire, and make a note of which color connects to which sensor lead.

Slide the sensor into the tube so that the wires extend from the end with the washer. The length of the sensor body should be parallel with the axis of the tube, and the top of the sensor should be flush with the end of the tube. Use RTV to secure the sensor inside the tube.

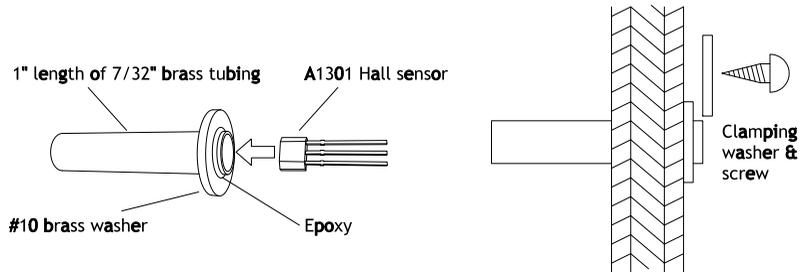


Figure 21. Mounting the Hall sensors.

The roll motion sensor will be held by a plywood sensor mount that spans between the two sensor support blocks on the pitch assembly. Make the sensor mount and temporarily position it on the support blocks. Place one of the brass tube mounted sensors in the sensor hole. Position the sensor mount so that the brass tube is centered in the magnet gap. Mark the mounting hole positions on the support blocks. Drill pilot holes then fasten the sensor mount to the support blocks with $\frac{3}{4}$ " #6 wood screws.

Mount the pitch assembly inside the joystick base box using $\frac{1}{4}$ " flat-head machine screws, washers, and nuts.

If you're planning on using the optional control loading springs, this is a good time to install them. If you're building a helicopter simulator you might not need them. If, on the other hand, you're building a fixed-wing sim, feeling a centering force through the joystick will add a bit more realism to the flight illusion.

The springs that provide the control loading force for joystick roll motion mount on the pitch assembly. One end of the spring hooks through the spring mounting bracket. The other end hooks through a loop of flexible steel cable. The other end of the cable loop goes around the screw on the far side of the pitch pivot.

A second pair of springs provides control loading for joystick pitch motion. These springs fasten to the box sides through use of eye bolts. A similar arrangement of steel cable loops connects the springs to the pitch assembly motion stop.

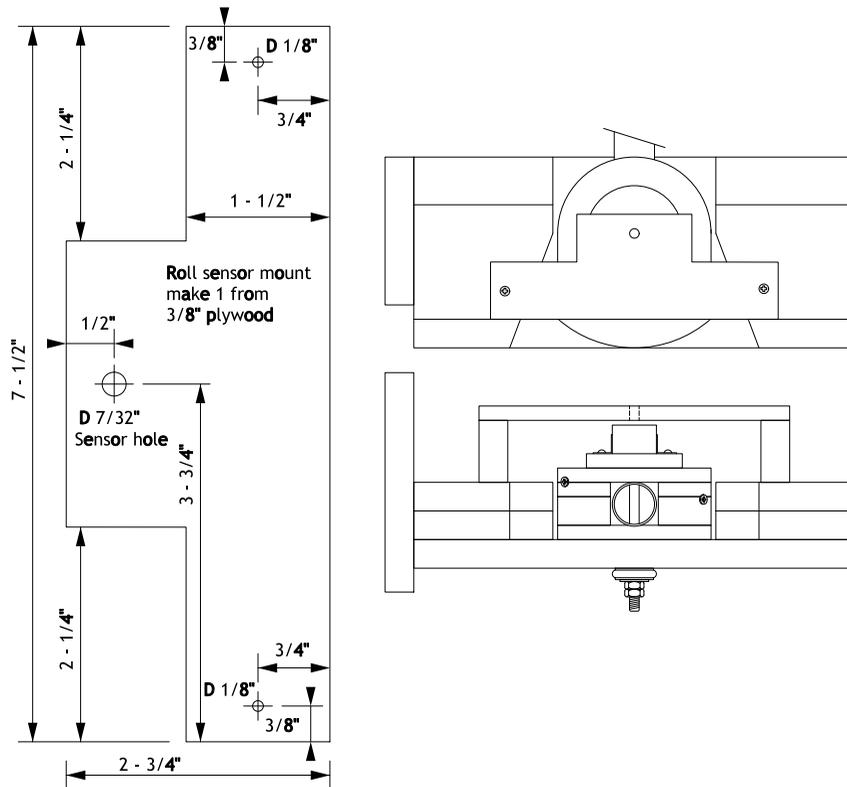


Figure 22. Roll sensor mount.

The size of the cable loops will depend on your choice of springs. Make the loop dimension such that the spring connected to it is just slightly extended when the joystick grip is moved to the farthest position away from the spring. The loops for the roll motion springs should be of the same length so the stick centers in the roll motion. Similarly, the loops for the pitch motion springs should be of equal lengths.

The radius of the curved portion of the pitch motion stop is the same as the radius of the roll pivot curve. Use identical springs to get equal control loading for both roll and pitch stick movements.

The upper portion of the joystick curves toward the pilot. For this we'll use a 90 degree, pre-bent piece of 1" thin wall electrical tubing spliced to the straight section embed in the roll pivot with a standard conduit coupling. Couplings come in two varieties: compression type and screw type. The screw type is less bulky.

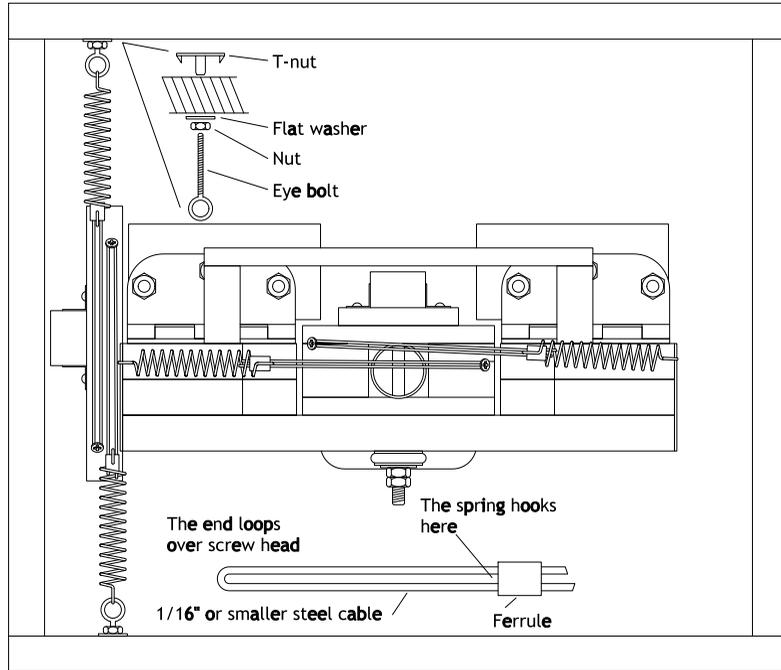


Figure 23. Adding control loading springs.

If you made the straight conduit section in the roll pivot extra long so you could trim it to size, use screws in the straight coupling to temporarily fasten the curved section to the end of the roll pivot conduit. After the remaining construction steps are completed, you can trim the conduit and permanently bond the conduit joint. Otherwise, use epoxy to permanently install the coupling. Use sandpaper to roughen the mating surfaces on the conduit and inside the coupling. This will greatly increase the strength of the epoxy bond. Make sure that the horizontal portion of the curved section is parallel to the centerline of your simulator floor.

The stick grip used for this project is from an old game-port style Thrustmaster® “Top Gun” joystick. Obsolete because of its interface, the grip is nonetheless a nicely made, if somewhat smaller, replica of the military B-8 flight grip. It provides us with a number of useful switches and gets a new life as part of this project. These vintage game controllers show up regularly at flea markets, junk shops, and on line auction sites.

Installing the grip on our joystick requires a 90 degree elbow along with some surgery. Remove the three screws from the side of the grip and carefully separate the two sides. Cut the wires going into the game controller base and discard the base. Take care that the switches don't fall out of the grip. There's not much holding them in place.

We'll use a 1" EMT 90 degree compression elbow to fasten the grip to our stick. The elbow has a nut on the male end. You can remove and discard it. Clean all the oil from the male threads. Use sandpaper to roughen the thread faces.

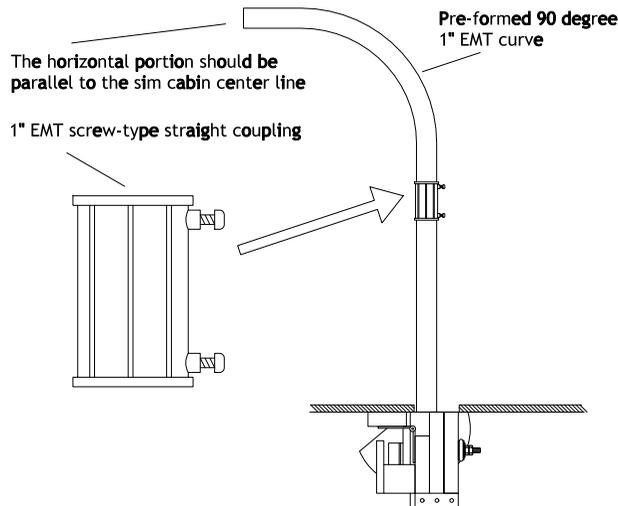


Figure 24. Aligning and fastening the curved section to the roll pivot.

Enlarge the hole in the bottom of the grip so that the male end of the elbow will fit into the grip. Use sandpaper to roughen the plastic of the left portion of the grip from the bottom up as far as the elbow sticks in. Snap the two halves of the grip back together. You don't need to put the screws back in.

Temporarily install the elbow and grip on the joystick. Orient the grip so it is most comfortable. If you're right handed you may find a 10 to 15 degree twist to the left beneficial. If left handed a twist to the right might suit you. If you can't make up your mind, line that puppy up with the centerline of your cockpit. Make alignment marks on the elbow and on the left hand half of the grip (the part with the switches).

Use epoxy to glue the male end of the elbow into the bottom of the left side of the grip. Use your alignment marks to get the right orientation.

We will not be gluing the right side of the grip to the elbow. It will be held on by the three screws. This allows us to open the grip when wiring the switches.

The easiest way to install the grip onto the joystick is to use the compression fitting on the elbow. It's easy, but looks bulky.

If you prefer a less bulky looking installation, remove the compression fitting from the elbow and prepare the threads inside the elbow for a layer of epoxy (clean, sand, etc.). Fill the threads with epoxy and let it harden. Sand the layer smooth and add more epoxy until the inner diameter of the elbow just matches the outer diameter of the joystick conduit. Don't glue the elbow onto the conduit. It should simply slide on snugly.

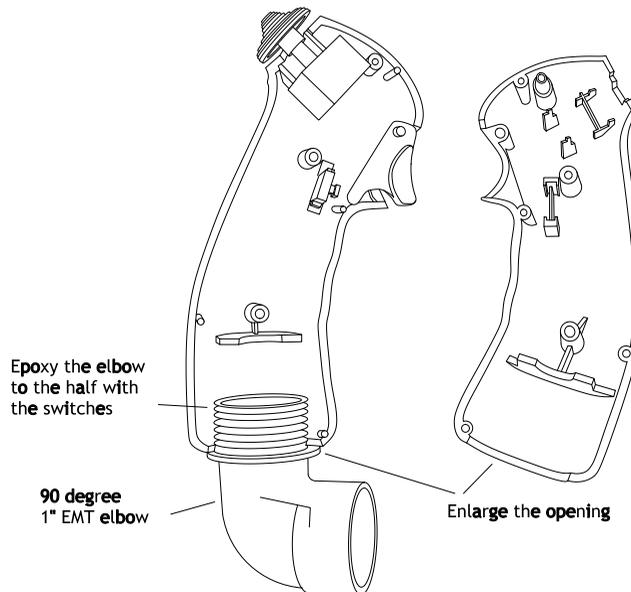


Figure 25. Joining the stick grip and the elbow.

Do another trial assembly to determine the most comfortable vertical orientation of the grip. Depending on your handedness, that may be 10 or 15 degrees left or right from vertical. Maintaining that alignment, drill a hole through the side of the elbow and through the conduit wall. The hole should be about $\frac{1}{4}$ " from the open end of the elbow and pass through the epoxy coated threads. Start with a $\frac{1}{16}$ " hole and enlarge in steps to $\frac{3}{16}$ ".

Epoxy a #8 machine nut²⁷ inside the conduit over the hole. Use sandpaper to roughen the surface and sides of the nut and of the inside of the conduit around the hole. Hold the nut in place while the epoxy cures with a machine screw coated with candle wax.

²⁷ An alternative is to use an aviation captive nut such as those available from Aircraft Spruce and Specialty, or a self-cinching "PEM" nut.

Once the epoxy has set up, repeat the process of drilling holes and installing another nut and screw on the other side of the elbow.

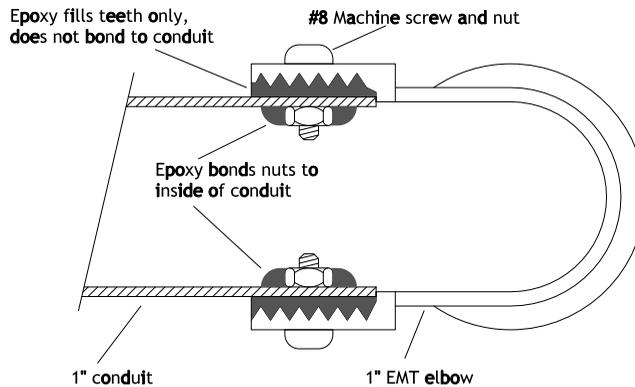


Figure 26. Joining the stick grip and the elbow.

Slide the Hall sensors into their respective mounting holes in the box side and pitch assembly. Each sensor will be held in place by a brass wood screw and washer that clamp the sensor against the wood.

To adjust the sensor orientation you'll need to apply power to the sensor and use a voltmeter to read the sensor output. Connect a +5 volt source to pin 2. Connect the voltmeter to pin 3. Pin 1 is the ground connection for both the power source and the voltmeter.

With the joystick in the center position turn the roll motion sensor so that its output voltage is 2.5 volts. Move the joystick to the right. The voltage should increase. If it decreases rotate the sensor 180 degrees and fine tune its position for 2.5 volts with the joystick in the center position.

Similarly adjust the position of the pitch sensor for a 2.5 volt output with the joystick in the center position. The voltage should increase when the stick is pushed forward. Rotate the sensor 180 degrees if the voltage decreases.

There are multiple interfacing options for connecting the joystick to your flight simulation computer. You can use interface products from companies like Phidgets, or you can use the USB electronics removed from game controller joysticks or game pads. These approaches are covered in more detail in the I/O Options chapter.

Bill of Materials

Quantity	Item	Sources, Notes
1	¾" 8" x 3' pine board	Preferably knot-free
	3/8" plywood	
2	3 ½" hinges with ¾" radius rounded corners	Inexpensive hinges will work okay, however, if you want minimal backlash in the stick, spend a bit more and buy hinges with minimal play.
2	Allegro A-1301 linear Hall sensors	
	7/32" OD brass hobby tubing	K&S Metals
4	#10 flat brass washer	
4	¾" diameter ceramic magnets	
2	3/8" #6 brass wood screws	
4	1" #10 wood screws	
1	¾" x ¼" flat steel washer	
1	¾" x ¼" brass washer	
1	3 - 1/2" x ¼" bolt	Used for roll pivot
2	4" flat steel corner brackets	
2	1 – 5/8" #8-32 threaded eye bolt	
2	#8 flat steel washer	
2	#8-32 machine nut	
2	#8-32 prong T-nut	
6	1 - 1/2" x ¼-20 flat-head machine screw	Used for hinges
6	2" x ¼-20 bolt	Used for hinges
14	¼-20 nut	
7	1" x ¼" flat washer	
1	5" galvanized steel lumber splice plate	
4	5/8" x 2 – ½" x .072" extension spring	For control loading
1	1" EMT	Comes in a 10' length
1	Flight grip from salvaged game joystick	
1	1" EMT 90 degree pre-bent section	
1	1" EMT 90 degree compression fitting	
1	1" EMT straight coupler, screw type	
1	Tube silicone kitchen & bathroom sealant	Your choice of color!
	Wood glue	A urethane glue like "Gorilla Glue" is a good choice.
	Fast setting epoxy	

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