

VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

BRNO UNIVERSITY OF TECHNOLOGY

FAKULTA ELEKTROTECHNIKY A KOMUNIKAČNÍCH TECHNOLOGIÍ
ÚSTAV RADIOELEKTRONIKY

FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION
DEPARTMENT OF RADIO ELECTRONICS

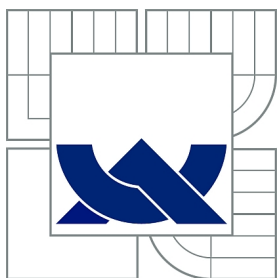
AUGMENTED REALITY APPLICATIONS IN EMBEDDED NAVIGATION
DEVICES

SEMESTRÁLNÍ PRÁCE
SEMESTRAL THESIS

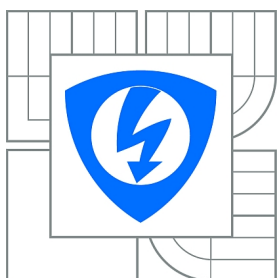
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BRNO 2013



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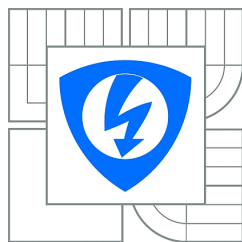
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VYSOKÉ UČENÍ
TECHNICKÉ V BRNĚ

Fakulta elektrotechniky
a komunikačních technologií

Ústav radioelektroniky

Semestrální práce

bakalářský studijní obor
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Augmented reality applications in embedded navigation devices

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BBCE: Examine practical use cases of the proposed navigation device, design applicable user interface.

DOPORUČENÁ LITERATURA:

[1] BIMBER, O.; RASKAR, R. Spatial augmented reality: merging real and virtual worlds. Wellesley: A K Peters, 2005, 369 p. ISBN 15-688-1230-2.

[2] Texas Instruments. OMAP 4460 Multimedia Device [online]. 2012 - [cit. 8. listopadu 2012]. Available: <http://www.ti.com/product/omap4460>.

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Vedoucí práce: doc. Ing. Tomáš Frýza, Ph.D.

Konzultanti semestrální práce:

doc. Ing. Tomáš Kratochvíl, Ph.D.

Předseda oborové rady

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ABSTRAKT

Tato práce se zabývá aplikací rozšířené reality v oblasti navigačních zařízení. Popisuje možnosti zpracování videa za účelem projekce virtuální scény pomocí dat získaných satelitním a inerciálním navigačním sybsystémem. Práce klade důraz na využití moderních hardwarových prostředků pro zpracování videa v mikroprocesorech pomocí grafických akcelerátorů. Součástí je návrh aplikace a realizace prototypu.

KLÍČOVÁ SLOVA

Rozšířená realita, satelitní navigace, inerciální měřící jednotka

ABSTRACT

This work deals with application of augmented reality in navigation devices. It describes possibilities of video processing, rendering a virtual scene by using data measured by satellite and inertial navigation subsystems. Special care is taken into account for use of modern graphic accelerator hardware available in microprocessors. Design of the application is supplemented with prototype realization.

KEYWORDS

Augmented reality, satellite navigation, inertial measurement unit

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PROHLÁŠENÍ

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Brno

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(podpis autora)

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Brno

.....

(podpis autora)

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Preface

Introduction

Source code for the application is available at
<https://github.com/martinjaros/augmented-reality-navigation>

Source code for this document is available at
<https://github.com/martinjaros/augmented-reality-navigation/tree/thesis>

HTML version of this document is available at
<http://martinjaros.github.io/augmented-reality-navigation>

1 Augmented reality

1.1 Design goals

Design goals and project overview

1.2 Hardware limitations

Developing an application for an embedded device faces a basic problem, as there are big differences between these devices it is hard to support the hardware and make the application portable. In order to reuse code and reduce application size, libraries are generally used. To provide enough abstraction operating system is used. There are many kernels specially tailored for embedded applications such as [FreeRTOS](#), [Linux](#) or proprietary [VxWorks](#), [Windows CE](#). Linux kernel has been chosen for this project.

Advantages of the Linux kernel

- free and open-source, well documented
- highly configurable and portable
- highly standardized, POSIX compliant
- large amount of drivers, good manufacturer support
- great community support, many tutorials

Disadvantages of the Linux kernel

- large code base
- steep learning curve
- high hardware requirements

While the application is designed to be highly portable depending only on the kernel itself, several devices has been chosen as the reference.

OMAP4460 application processor¹

- two ARM Cortex-A9 SMP general-purpose processors
- IVA 3 video accelerator, 1080p capable
- image signal processor, 20MP capable
- SGX540 3D graphics accelerator, OpenGL ES 2.0 compatible
- HDMI v1.3 video output

MPU-9150 motion tracking device²

- embedded MPU-6050 3-axis gyroscope and accelerometer
- embedded AK8975 3-axis digital compass
- fully programmable, I²C interface

OV5640 image sensor³

- 1080p, 5MP resolution
- raw RGB or YUV output

¹OMAP4460 Technical reference manual
<http://www.ti.com/litv/pdf/swpu235aa>

²MPU-9150 Product specification
http://invensense.com/mems/gyro/documents/PS-MPU-9150A-00v4_3.pdf

³OV5640 Product brief
http://www.ovt.com/download_document.php?type=sensor&sensorid=93

2 Application

2.1 Linux kernel

Programs running in Linux are divided into two groups, *kernel-space* and *user-space*. Only kernel and its runtime modules are allowed to execute in *kernel-space*, while all other programs runs as processes in *user-space*.

kernel-space

- real-time CPU usage
- physical memory access

user-space

- scheduled CPU usage
- virtual memory access

In Linux each process runs in a sandbox, isolated from the rest of the system. Processes access virtual memory unique to them, they cannot access memory assigned for other processes nor memory managed by the kernel. Their execution is not real-time, but they are assigned restricted processor time by the kernel. They may communicate with outside environment by several means

- Arguments and environment variables
- Standard input, output and error output
- Virtual File System
- Signals
- Sockets
- Memory mapping

Each process is ran with several arguments in a specific environment with three default file descriptors. For example running

```
VARIABLE=value ./executable argument1 argument2 <input 1>output 2>error
```

will execute *executable* with environment variable *VARIABLE* of value *value* with two arguments *argument1* and *argument2*. Standard input will be read from file *input* while regular output will be written to file *output* and error output to file *error*. This process may further communicate by accessing files in the Virtual File System, kernel may expose useful process information for example via **procfs** file-system usually mounted at **/proc**. Other types of communication are signals (which may be sent between processes or by kernel) and network sockets. With internal network loop-back device, network style inter process

communication is possible using standard protocols (UDP, TCP, ...). Memory mapping is a way to request access to some part of the physical memory.

Processes may run with numerous threads, each thread has preemptively scheduled execution. Threads share memory within a process, memory access to these shared resources must be done with care to avoid race conditions and data corruption. Kernel provides *mutex* objects to lock threads and avoid simultaneous memory access. Each shared resource should be attached to a *mutex*, which is locked during access to this resource. Thread must not lock *mutex* while still holding lock to this or any other *mutex* in order to avoid dead-locking.

Source example for using posix threads

```
1  #include <stdio.h>
2  #include <pthread.h>
3
4  void *worker1(void *arg)
5  {
6      pthread_mutex_t *mutex = (pthread_mutex_t*)arg;
7      static char buffer[64];
8
9      // Lock mutex to restrict access to stdin and stdout
10     pthread_mutex_lock(mutex);
11     printf("This is worker 1, enter something: ");
12     scanf("%64s", buffer);
13     pthread_mutex_unlock(mutex);
14
15     return (void*)buffer;
16 }
17
18 void *worker2(void *arg)
19 {
20     pthread_mutex_t *mutex = (pthread_mutex_t*)arg;
21     static char buffer[64];
22
23     // Lock mutex to restrict access to stdin and stdout
24     pthread_mutex_lock(mutex);
25     printf("This is worker 2, enter something: ");
26     scanf("%64s", buffer);
27     pthread_mutex_unlock(mutex);
28
29     return (void*)buffer;
30 }
31
32 int main()
33 {
34     pthread_mutex_t mutex;
```

```

35 pthread_t thread1, thread2;
36 char *retval1, *retval2;
37
38 // Initialize two threads with shared mutex, use default parameters
39 pthread_mutex_init(&mutex, NULL);
40 pthread_create(&thread1, NULL, worker1, (void*)&mutex);
41 pthread_create(&thread2, NULL, worker2, (void*)&mutex);
42
43 // Wait for both threads to finish and display results
44 pthread_join(thread1, (void**)&retval1);
45 pthread_join(thread2, (void**)&retval2);
46 printf("Thread 1 returned with `%s`.\n", retval1);
47 printf("Thread 2 returned with `%s`.\n", retval2);
48
49 pthread_mutex_destroy(&mutex);
50 return 0;
51 }

```

Linux kernel has monolithic structure, so all device drivers resides in the kernel. From application point of view, this means that all peripheral access must be done through the standard library and Virtual File System. Individual devices are accessible as device files defined by major and minor number typically located at `/dev`. These files could be created automatically by kernel (`devtmpfs` file-system), by daemon (`udev(8)`), or manually by `mknod(1)`. Complete kernel device model is exported as `sysfs` file-system and typically mounted at `/sys`.

Function name	Access type	Typical usage
<code>select()</code> , <code>poll()</code>	event	Synchronization, multiplexing, event handling
<code>ioctl()</code>	structure	Configuration, register access
<code>read()</code> , <code>write()</code>	stream	Raw data buffers, byte streams
<code>mmap()</code>	block	High throughput data transfers

Table 1: Available functions for working with device file descriptors

For example let's assume a generic peripheral device connected by the I²C bus. First, to tell kernel there is such a device, the `sysfs` file-system may be used

```
echo $DEVICE_NAME $DEVICE_ADDRESS > /sys/bus/i2c/devices/i2c-1/new_device
```

This should create a special file in `/dev`, which should be opened by `open()` to get a file descriptor for this device. Device driver may export some `ioctl` requests, each request is

defined by a number and a structure passed between the application and the kernel. Driver should define requests for controlling the device, maybe accessing its internal registers and configuring a data stream. Each request is called by

```
ioctl(fd, REQNUM, &data);
```

where *fd* is the file descriptor, *REQNUM* is the request number defined in the driver header and *data* is the structure passed to the kernel. This request will be synchronously processed by the kernel and the result stored in the *data* structure. Let's assume this devices has been configured to stream an integer value every second to the application. To synchronize with this timing application may use

```
struct pollfd fds = {fd, POLLIN};  
poll(&fds, 1, -1);
```

which will block infinitely until there is a value ready to be read. To actually read it,

```
int buffer[1];  
ssize_t num = read(fd, buffer, sizeof(buffer));
```

will copy this value to the buffer. Copying causes performance issues if there are very large amounts of data. To access this data directly without copying them, application has to map physical memory used by the driver. This allows for example direct access to a DMA channel, it should be noted that this memory may still be needed by kernel, so there should be some kind of dynamic access restriction, possibly via *ioctl* requests (this would be driver specific).

2.2 Video subsystem

Video support in Linux kernel is maintained by the LinuxTV⁴ project, it implements the *videodev2* kernel module and defines the *V4L2* interface. Modules are part of the mainline kernel at `drivers/media/video/*` with header `linux/videodev2.h`. The core module is enabled by the *VIDEO_V4L2* configuration option, specific device drivers should be enabled by their respective options. *V4L2* is the latest revision and is the most widespread video interface throughout Linux, drives are available from most hardware manufactures and usually mainlined or available as patches. The Linux Media Infrastructure API⁵ is a well documented interface shared by all devices. It provides abstraction layer for various device implementations, separating the platform details from the applications. Each video device has its device file and is controlled via *ioctl* calls. For streaming standard I/O functions are supported, but the memory mapping is preferred, this allows passing only pointers between the application and the kernel, instead of unnecessary copying the data around.

Name	Description
------	-------------

⁴LinuxTV project
<http://linuxtv.org/>

⁵Linux Media Infrastructure API
<http://linuxtv.org/downloads/v4l-dvb-apis/>

<code>VIDIOC_QUERYCAP</code>	Query device capabilities
<code>VIDIOC_G_FMT</code>	Get the data format
<code>VIDIOC_S_FMT</code>	Set the data format
<code>VIDIOC_REQBUFS</code>	Initiate memory mapping
<code>VIDIOC_QUERYBUF</code>	Query the status of a buffer
<code>VIDIOC_QBUF</code>	Enqueue buffer to the kernel
<code>VIDIOC_DQBUF</code>	Dequeue buffer from the kernel
<code>VIDIOC_STREAMON</code>	Start streaming
<code>VIDIOC_STREAMOFF</code>	Stop streaming

Table 2: ioctl calls defined in `linux/videodev2.h`

Application sets the format first, then requests and maps buffers from the kernel. Buffers are exchanged between the kernel and the application. When the buffer is enqueued, it will be available for the kernel to capture data to it. When the buffer is dequeued, kernel will not access the buffer and application may read the data. After all buffer are enqueued application starts the stream. Polling is used to wait for the kernel until it fills the buffer, buffer should not be accessed simultaneously by the kernel and the application. After processing the buffer, application should return it back to the kernel queue. Note that buffers should be properly unmapped by the application after stopping the stream.

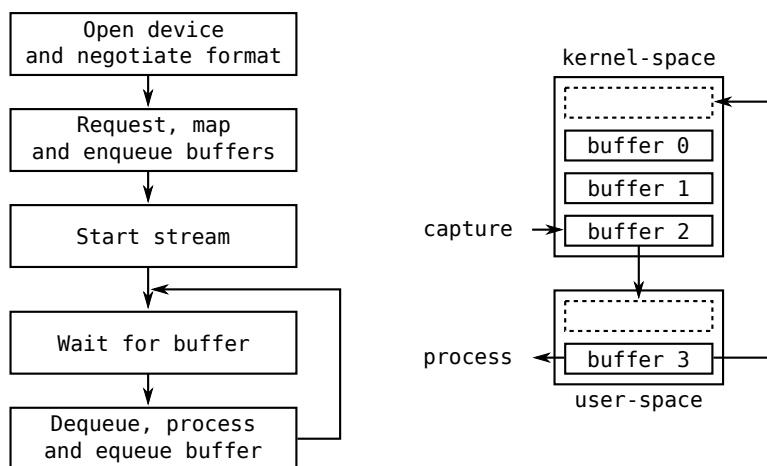


Figure 1: V4L2 capture

Source example for simple video capture

```

1 #include <fcntl.h>
2 #include <unistd.h>

```

```

3  #include <poll.h>
4  #include <sys/mman.h>
5  #include <sys/ioctl.h>
6  #include <linux/videodev2.h>
7
8  int main()
9  {
10     // Open device
11     int fd = open("/dev/video0", O_RDWR | O_NONBLOCK);
12
13     // Set video format
14     struct v4l2_format format =
15     {
16         .type = V4L2_BUF_TYPE_VIDEO_CAPTURE,
17         .fmt =
18         {
19             .pix =
20             {
21                 .width = 320,
22                 .height = 240,
23                 .pixelformat = V4L2_PIX_FMT_RGB32,
24                 .field = V4L2_FIELD_NONE,
25                 .colorspace = V4L2_COLORSPACE_SMPTE170M,
26             },
27         },
28     };
29     ioctl(fd, VIDIOC_S_FMT, &format);
30
31     // Request buffers
32     struct v4l2_requestbuffers requestbuffers =
33     {
34         .type = V4L2_BUF_TYPE_VIDEO_CAPTURE,
35         .memory = V4L2_MEMORY_MMAP,
36         .count = 4,
37     };
38     ioctl(fd, VIDIOC_REQBUFS, &requestbuffers);
39     void *pbuffers[requestbuffers.count];
40
41     // Map and enqueue buffers
42     int i;
43     for(i = 0; i < requestbuffers.count; i++)
44     {
45         struct v4l2_buffer buffer =
46         {
47             .type = V4L2_BUF_TYPE_VIDEO_CAPTURE,

```

```

48         .memory = V4L2_MEMORY_MMAP,
49         .index = i,
50     };
51     ioctl(fd, VIDIOC_QUERYBUF, &buffer);
52     pbuffers[i] = mmap(NULL, buffer.length,
53                         PROT_READ | PROT_WRITE, MAP_SHARED,
54                         fd, buffer.m.offset);
55     ioctl(fd, VIDIOC_QBUF, &buffer);
56 }
57
58 // Start stream
59 enum v4l2_buf_type buf_type = V4L2_BUF_TYPE_VIDEO_CAPTURE;
60 ioctl(fd, VIDIOC_STREAMON, &buf_type);
61
62 while(1)
63 {
64     // Synchronize
65     struct pollfd fds =
66     {
67         .fd = fd,
68         .events = POLLIN
69     };
70     poll(&fds, 1, -1);
71
72     // Dump buffer to stdout
73     struct v4l2_buffer buffer =
74     {
75         .type = V4L2_BUF_TYPE_VIDEO_CAPTURE,
76         .memory = V4L2_MEMORY_MMAP,
77     };
78     ioctl(fd, VIDIOC_DQBUF, &buffer);
79     write(1, pbuffers[buffer.index], buffer.bytesused);
80     ioctl(fd, VIDIOC_QBUF, &buffer);
81 }
82 }

```

The image format is specified using the little-endian four-character code (FOURCC). V4L2 defines⁶ several formats and provides `v4l2_fourcc()` macro to create a format code from four characters. As described later in the [graphics subsystem](#) chapter, graphics uses natively the *RGB4* format. This format is defined as a single plane with one sample per pixel and four bytes per sample. These bytes represents red, green and blue channel values respectively. Image size is therefore *width · height · 4* bytes. Many image sensors however support *YUV*

⁶V4L2 image format definitions
<http://linuxtv.org/downloads/v4l-dvb-apis/pixfmt.html>

color-space, for example the *YU12* format. This one is defined as three planes, the first plane with one luminance sample per pixel and the second and third plane with one chroma sample per four pixels (2 pixels per row, interleaved). Each sample has one byte, this format is also referenced as *YUV 4:2:0* and its image size is $width \cdot height \cdot 1.5$ bytes. The luminance and chroma of a pixel is defined as

$$(1) E_Y = W_R \cdot E_R + (1 - W_R - W_B) \cdot E_G + W_B \cdot E_B$$

$$(2) E_{C_r} = \frac{0.5(E_R - E_Y)}{1 - W_R}$$

$$(3) E_{C_b} = \frac{0.5(E_B - E_Y)}{1 - W_B}$$

where E_R , E_G , E_B are normalized color values and W_R , W_B are their weights. ITU-R Rec. BT.601⁷ defines weights as 0.299 and 0.114 respectively, it also defines how they are quantized

$$(4) Y = 219E_Y + 16$$

$$(5) C_r = 224E_{C_r} + 128$$

$$(6) C_b = 224E_{C_b} + 128$$

To calculate R, G, B values from Y, Cr, Cb values, inverse formulas must be used

$$(7) E_Y = \frac{Y - 16}{219}$$

$$(8) E_{C_r} = \frac{C_r - 128}{224}$$

$$(9) E_{C_b} = \frac{C_b - 128}{224}$$

$$(10) E_R = E_Y + 2E_{C_r}(1 - W_R)$$

$$(11) E_G = E_Y - 2E_{C_r} \frac{W_R - W_R^2}{W_G} - 2E_{C_b} \frac{W_B - W_B^2}{W_G}$$

$$(12) E_B = E_Y + 2E_{C_b}(1 - W_B)$$

It should be noted that not all devices may use the BT.601 recommendation, V4L2 refers to it as *V4L2_COLORSPACE_SMPTE170M* in the *VIDIOC_S_FMT* request structure.

GLSL implementation of the YUV to RGB conversion (see [graphics subsystem](#) chapter for description of GLSL)

⁷ITU-R Recommendation BT.601-7

http://www.itu.int/dms_pubrec/itu-r/rec/bt/R-REC-BT.601-7-201103-I!!PDF-E.pdf

```

1 uniform sampler2D texY, texU, texV;
2 varying vec2 texCoord;
3
4 void main()
5 {
6     float y = texture2D(texY, texCoord).a * 1.1644 - 0.062745;
7     float u = texture2D(texU, texCoord / 2).a - 0.5;
8     float v = texture2D(texV, texCoord / 2).a - 0.5;
9
10    gl_FragColor = vec4(
11        y + 1.596 * v,
12        y - 0.39176 * v - 0.81297 * u,
13        y + 2.0172 * u,
14        1.0);
15 }

```

There is a module *v4l2loopback*⁸ which creates a video loop-back device, similar to network loop-back, allowing piping two video applications together. This is very useful not only for testing, but also for implementation of intermediate decoders. GStreamer⁹ is a powerful multimedia framework widespread in Linux distributions, composed of a core infrastructure and hundreds of plug-ins. This command will create synthetic *RGB4* video stream for the application, useful for testing

```

modprobe v4l2loopback
gst-launch videotestsrc pattern=solid-color foreground-color=0xE0F0E0 ! \
"video/x-raw,format=RGBx,width=800,height=600,framerate=20/1" \
! v4l2sink device=/dev/video0

```

Texas Instruments distributes a meta package¹⁰ for their OMAP platform featuring all required modules and DSP firmware. This includes kernel modules for *SysLink* inter-chip communication library, *Distributed Codec Engine* library and *ducati* plug-in for GStreamer. With the meta-package installed, it is very easy and efficient to implement mainstream encoded video formats. For example following command will create GStreamer pipeline to receive video payload over a network socket from an IP camera, decode it and push it to the loop-back device for the application. MPEG-4 AVC (H.264) decoder of the IVA 3 is used in this example.

```

modprobe v4l2loopback
gst-launch udpsrc port=5004 caps=\
"application/x-rtp,media=video,payload=96,clock-rate=90000,encoding-name=H264" \
! rtph264depay ! h264parse ! ducatih264dec ! v4l2sink device=/dev/video0

```

⁸V4L2 loopback device module
<https://github.com/umlaeute/v4l2loopback>

⁹GStreamer home page
<http://gstreamer.freedesktop.org/>

¹⁰TI OMAP trunk PPA
<https://launchpad.net/~tiomap-dev/+archive/omap-trunk>

On OMAP4460 this would consume only about 15% of the CPU time as the decoding is done by the IVA 3 video accelerator in parallel to the CPU which only passes pointers around and handles synchronization. Output format is *NV12* which is similar to *YU12* format described earlier, but there is only one chroma plane with two-byte samples, first byte being the U channel and the second byte the V channel, sampling is same 4:2:0. The YUV to RGB color space conversion must take place here, preferably implemented on the GPU as described above.

Cortex-A9 cores on the OMAP4460 also have the NEON co-processor, capable of vector floating point math. Although not very supported by the GCC C compiler, there are many assembly written libraries implementing coders with the NEON acceleration. For example the *libjpeg-turbo*¹¹ library is implementing the *libjpeg* interface. It is useful for USB cameras, as the USB throughput is not high enough for raw high definition video, but is sufficient with JPEG coding (as most USB cameras supports JPEG, but does not support H.264). 1080p JPEG stream decoded with this library via its GStreamer plug-in will consume about 90% of the single CPU core time (note that there are two CPU cores available). However, comparable to the AVC, JPEG encoding will cause visible quality degradation in the raw stream (video looks grainy).

2.3 Graphics subsystem

Graphics stack, OpenGL ES 2.0

¹¹libjpeg-turbo library
<http://www.libjpeg-turbo.org/>

2.4 Inertial measurement subsystem

Application needs to know its spatial orientation for rendering, there three devices which may provide such information, gyroscope, compass (magnetometer) and accelerometer. Hardware details about these devices are in the [hardware](#) chapter.

2.4.1 Industrial I/O module

Industrial I/O module

2.4.2 DCM algorithm

Gyroscope measures angular speed around device axes, it offers high differential precision and fast sampling rate, however it suffers slight zero offset error. Device attitude can be obtained simply by integrating measured angular rates, provided that initial attitude is known. The angular rate is defined as

$$(13) \quad \vec{\omega}_g = \frac{d}{dt} \vec{\Phi}_{(t)}$$

so the angular displacement between last two samples is

$$(14) \quad [\Phi_x, \Phi_y, \Phi_z] = [\omega_x, \omega_y, \omega_z] \cdot \Delta t$$

This can be described as a rotation

$$(15) \quad \mathbf{R}_{gyro} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\Phi_x) & -\sin(\Phi_x) \\ 0 & \sin(\Phi_x) & \cos(\Phi_x) \end{bmatrix} \times \begin{bmatrix} \cos(\Phi_y) & 0 & \sin(\Phi_y) \\ 0 & 1 & 0 \\ -\sin(\Phi_y) & 0 & \cos(\Phi_y) \end{bmatrix} \times \begin{bmatrix} \cos(\Phi_z) & -\sin(\Phi_z) & 0 \\ \sin(\Phi_z) & \cos(\Phi_z) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

With Δt close to zero a small-angle approximation may be used to simplify $\cos(x) = 1$, $\sin(x) = x$

$$(16) \quad \mathbf{R}_{gyro} \doteq \begin{bmatrix} 1 & -\Phi_z & \Phi_y \\ \Phi_x\Phi_y + \Phi_z & 1 - \Phi_x\Phi_y\Phi_z & -\Phi_x \\ \Phi_x\Phi_z - \Phi_y & \Phi_x + \Phi_y\Phi_z & 1 \end{bmatrix}$$

Let's define the directional cosine matrix describing device attitude

$$(17) \quad \mathbf{DCM} = \begin{bmatrix} \hat{\mathbf{I}} \cdot \hat{\mathbf{x}} & \hat{\mathbf{I}} \cdot \hat{\mathbf{y}} & \hat{\mathbf{I}} \cdot \hat{\mathbf{z}} \\ \hat{\mathbf{J}} \cdot \hat{\mathbf{x}} & \hat{\mathbf{J}} \cdot \hat{\mathbf{y}} & \hat{\mathbf{J}} \cdot \hat{\mathbf{z}} \\ \hat{\mathbf{K}} \cdot \hat{\mathbf{x}} & \hat{\mathbf{K}} \cdot \hat{\mathbf{y}} & \hat{\mathbf{K}} \cdot \hat{\mathbf{z}} \end{bmatrix} = \begin{bmatrix} \hat{\mathbf{I}}_{xyz} \\ \hat{\mathbf{J}}_{xyz} \\ \hat{\mathbf{K}}_{xyz} \end{bmatrix}$$

where $\hat{\mathbf{I}}$ points to the north, $\hat{\mathbf{J}}$ points to the east, $\hat{\mathbf{K}}$ points to the ground and therefore $\hat{\mathbf{I}} = \hat{\mathbf{J}} \times \hat{\mathbf{K}}$. Roll, pitch and yaw angels in this matrix are

$$(18) \quad \gamma = -\arctan_2\left(\frac{\mathbf{DCM}_{23}}{\mathbf{DCM}_{33}}\right)$$

$$(19) \quad \beta = \arcsin(\mathbf{DCM}_{13})$$

$$(20) \quad \alpha = -\arctan_2\left(\frac{\mathbf{DCM}_{12}}{\mathbf{DCM}_{11}}\right)$$

DCM can be computed by applying consecutive rotations over time

$$(21) \quad \mathbf{DCM}_{(t)} = \mathbf{R}_{gyro(t)} \times \mathbf{DCM}_{(t-1)}$$

If the sampling rate is high enough (over 1kHz at least), this method is very accurate and has good dynamics over short periods of time, but in longer runs errors integrated during processing will cause serious drift (both numerical errors and zero offset errors). To mitigate these problems accelerometer and compass has to be used to provide the initial attitude and to fix the drift over time. Accelerometer measures external mechanical forces applied to the device together with gravitational force. However precision of these devices are generally worse and they have slower sampling rates. If there are no extern forces, it will measure the gravitational vector directly, thus providing the third row of the DCM.

$$(22) \quad \vec{\mathbf{a}}_{acc} = g \hat{\mathbf{K}}_{xyz} + \frac{\vec{\mathbf{F}}}{m}$$

Angular error is

$$(23) \quad \delta_{ERR} = \arccos\left(\frac{\vec{\mathbf{a}}_{acc}}{|\vec{\mathbf{a}}_{acc}|} \cdot \hat{\mathbf{K}}_{xyz}\right)$$

increasing nonlinearly with magnitude of the force \vec{F} . When there is an external force applied, which is significant relative to gravitational force, measurements will degrade rapidly. There is a singularity during the free fall. This error may be corrected by using device speed measured by satellite navigation system with high sample rate (over 10Hz).

$$(24) \quad \widehat{\mathbf{K}}_{xyz} = \frac{\vec{a}_{acc} - \frac{d}{dt} \vec{v}_{GPS}}{g}$$

Magnetometer has similar properties, it measures magnetic flux density of the field the device is within. This should ideally result in a vector pointing to the north, therefore providing the first row of the DCM.

$$(25) \quad \vec{I}_{xyz} = \frac{\vec{B}_{corr}}{|\vec{B}_{corr}|}$$

Magnetometers have even slower sampling rates and far worse precision, this is caused mainly by the field itself. First there are many local distortions in the Earth magnetic field, caused by nearby metal objects, they can be divided into hard-iron and soft-iron effects. Hard-iron distortion (sometimes referred as magnetic deviation) is caused by materials that produces magnetic field, that is added to the Earth magnetic field. This field can be simply subtracted to compensate this error

$$(26) \quad \vec{B}_{corr1} = \vec{B}_{mag} - \frac{1}{2} [\min(B_x) + \max(B_x), \min(B_y) + \max(B_y), \min(B_z) + \max(B_z)]$$

The soft-iron distortion is caused by soft magnetic materials, which influences the field in a way that is not additive. It may be observed as an ellipse when the device is turned around and the measured values are plotted. To compensate for this error, values has to be processed in a way that transforms the ellipse back to the circle. Further more the magnetic field of the Earth itself does not point to the geographic north, but is rotated by an angle specific to the location on the Earth surface. Magnetic inclination is the vertical portion of this rotation causing magnetic vector to incline to the ground, it may be fixed by using measurements from the accelerometer to make the magnetic vector perpendicular to the gravitational vector.

$$(27) \quad \vec{B}_{corr2} = \widehat{\mathbf{K}}_{xyz} \times \vec{B}_{mag} \times \widehat{\mathbf{K}}_{xyz}$$

Magnetic declination (sometimes referred as magnetic variation) is the horizontal portion of this rotation and is sometimes provided by the satellite navigation systems. To correct for this error, measured values have to be rotated by the inverse angle.

$$(28) \quad \vec{B}_{corr3} = \vec{B}_{mag} \begin{bmatrix} \cos(var) & \sin(var) \\ -\sin(var) & \cos(var) \end{bmatrix}$$

Weighted average should be used to combine the DCM calculated by gyroscope and the DCM composed of corrected accelerometer and magnetometer measurements, actual weights must be estimated by trial and error.

2.5 Satellite navigation subsystem

TTY module, stty, socat, GPS, NMEA 0183

3 Hardware

Existing modules, designs

4 Conclusion

Conclusion

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