COMP0130: ROBOT VISION AND NAVIGATION

Coursework 1: Integrated Navigation for a Robotic Lawnmower

Aim

The aim of this coursework is to give you experience of fusing data from a variety of sensors to obtain an optimal position, velocity and heading solution. This builds on Workshops 1, 2 and 3.

Assessment

This coursework is worth 33% of the module, or 4.95 credits.

Background

A robotic lawnmower somewhere in London is equipped with a GNSS receiver, wheel speed sensors, magnetic compass and a low-cost MEMS gyroscope to determine its position, velocity and heading so that it may determine an efficient route. You have been provided with (simulated) data from all of these sensors. You should assume that all sensors exhibit errors. The lawnmower is also equipped with ultrasound sensors for obstacle avoidance, though this is outside the scope of the exercise.

Your Task

You task is to use the sensor data to compute the best possible horizontal position, horizontal velocity and heading solution for the lawnmower at each point in time. There are a number of different approaches which result in navigation solutions of differing accuracy and reliability. More sophisticated approaches will be rewarded with higher marks. You are *not* expected to use everything you have learnt during the module; it's up to you to select the most appropriate method.

Each group must write their own software to do this. You are welcome to adapt some of the software you wrote for the workshops. Note that the GNSS satellites received may be different. You will probably find it easiest to use Matlab, but you may use another language if you wish.

It is recommended that you initially generate one solution using GNSS only and another solution using the other sensors. You can then compare these with each other to see if you have made any mistakes. When you are happy with these separate solutions, you should then generate a final solution using all of the data.

There is no need to worry about the details of the lawnmower design, such as the steering mechanism.

Two deliverables must be uploaded to Moodle by **16:00 on Tuesday 8 February 2024**. The first is a motion profile file containing your position, velocity and heading solution. The second is a report describing your method and results. Your source code must be attached to the report as an appendix. Do not submit .rar files.

Further details follow.

Data Files Supplied

You have been provided on Moodle with three data files, all in comma-separated variable (CSV) format:

- In the pseudo-ranges file, the first column contains the time tag in seconds and the first row contains the satellite numbers. The remaining rows and columns contain the corresponding pseudo-range measurements in metres.
- In the pseudo-range rates file, the first column contains the time in seconds and the first row contains the satellite numbers. The remaining rows and columns contain the corresponding pseudo-range rate measurements in metres per second.
- In the dead-reckoning file, column 1 contains time in seconds, columns 2 to 5 contain the wheel-speed measurements from sensors 1 to 4 in metres per second. Column 6 contains the gyroscope angular rate measurements in radians per second. Column 7 contains the heading measurements in degrees from the magnetic compass.

Sensor Specifications

The following **GNSS** error specifications should be assumed under typical conditions:

- Signal in space error standard deviation: 1m.
- Residual ionosphere error standard deviation at zenith: 2m.
- Residual troposphere error standard deviation at zenith: 0.2m.
- Code tracking and multipath error standard deviation: 2m.
- Range rate tracking and multipath error standard deviation: 0.02 m/s.

You can assume that the GNSS measurements have already been corrected for the ionosphere, troposphere and satellite clock errors. The values given above describe the errors remaining after the corrections have been applied as these corrections are not perfect. Note that ionosphere and troposphere errors are larger at lower elevation angles.

Reasonable, though not optimal, performance can be achieved by assuming a noise standard deviation of 10m on all pseudo-range measurements and 0.05 m/s on all pseudo-range rate measurements. GNSS measurements apply to the instant at which they are time tagged.

Please be aware that additional large GNSS measurement errors can occur in the presence of non-line-of-sight reception or satellite faults.

You can assume the following properties for the GNSS receiver clock:

- Initial receiver clock offset standard deviation: 100 000 m.
- Receiver clock drift standard deviation: 200 m/s.
- Clock phase PSD: 0.01 m^2s^{-3}.
- Clock frequency PSD: 0.04 m^2s^{-1}.

Remember that you need to use least-squares to estimate the receiver clock errors before you can initialise an extended Kalman filter.

The locations of the **wheel speed sensors** with respect to the GNSS antenna (sometimes known as 'lever arms') are as follows:

1) 0.3m forwards, −0.2m right;
2) 0.3m forwards, 0.2m right;
3) −0.2m forwards, −0.2m right;
4) −0.2m forwards, 0.2m right.

Note that the rear wheels are the driving wheels.

The following sensor specifications may be assumed for all wheel speed sensors to account for the effects of varying tyre radii and wheel slip:

- Scale factor error standard deviation: 3%.
- Noise standard deviation: 0.05 m/s.

The wheel speed sensor outputs are also quantised at a level of 0.02 m/s.

The **gyroscope** can be assumed to have the following error characteristics:

- A bias standard deviation of 1 degree per second (the bias can be assumed to be roughly constant each time the gyroscope is used).
- A scale factor error standard deviation of 1%.
- A cross-coupling error standard deviation of 0.1%.
- A random noise standard deviation of 10^{-4} radians per second.
- A quantisation level of 2×10^{-4} radians per second.

Note that these gyro errors are much larger than the rotation rate of the Earth. Therefore, if you neglect the Earth's rotation when you process the gyro measurements, it won't have much effect on your results.

Both wheel speed and gyroscope measurements are averaged over the interval between the previous and current time tags. Reasonable, though not optimal, results can be achieved by assuming a power spectral density of 0.01 m^2/s^3 for the wheel speed measurement errors and 3×10^{-6} rad^2/s for the gyro measurement errors apart from the bias. Thus, every second, the velocity error variance grows by 0.01 m^2/s^2 and the heading error variance by 3×10^{-6} rad^2.

The **magnetic heading** solution can be assumed subject to a noise-like error with a standard deviation of $4°$ in the absence of localised magnetic anomalies. You can assume that the magnetic heading has already been calibrated for the effects of the lawnmower's hard-iron and soft-iron magnetism. Magnetic heading measurements apply to the instant at which they are time tagged.

Software Resources Supplied

A number of Matlab files have been provided for your use on Moodle. You must use Satellite_position_and_velocity.m to obtain the correct satellite positions and velocities in Cartesian Earth-centred Earth-fixed (ECEF) coordinates. Use of the other files is optional. They are:

- CTM_to_Euler.m converts attitude from a coordinate transformation matrix to Euler angles.
- Define_Constants.m sets up a number of useful constants.
- ECEF_to_NED.m computes geodetic, latitude, longitude and height; Earth-referenced velocity in the north, east and down directions; and the body to north-east-down coordinate transformation matrix from the Cartesian ECEF position; Earth-referenced velocity resolved in the ECEF frame; and the body to ECEF coordinate transformation matrix.
- Euler_to_CTM.m converts attitude from Euler angles to a coordinate transformation matrix.
- Gravity_ECEF computes the acceleration due to gravity resolved in the ECEF frame.

- NED_to_ECEF.m computes the Cartesian ECEF position; Earth-referenced velocity resolved in the ECEF frame; and the body to ECEF coordinate transformation matrix from geodetic, latitude, longitude and height; Earth-referenced velocity in the north, east and down directions; and the body to north-east-down coordinate transformation matrix.
- pv_ECEF_to_NED.m computes geodetic, latitude, longitude and height and Earth-referenced velocity in the north, east and down directions from the Cartesian ECEF position and Earth-referenced velocity resolved in the ECEF frame.
- pv_NED_to_ECEF.m computes the Cartesian ECEF position and Earth-referenced velocity resolved in the ECEF frame from geodetic, latitude, longitude and height and Earth-referenced velocity in the north, east and down directions.
- Radii_of_curvature.m computes the meridian and transverse radii of curvature.
- Skew_symmetric.m computes the skew-symmetric matrix of the input vector.

Requirements for Deliverable 1: Motion Profile File

This must be in CSV format and comprise the following six columns
1) Time in seconds – this must match the data files.
2) Geodetic latitude in degrees (at least 6 decimal places).
3) Geodetic longitude in degrees (at least 6 decimal places).
4) North velocity in metres per second (at least 3 decimal places).
5) East velocity in metres per second (at least 3 decimal places).
6) Heading in degrees (at least 2 decimal places).

Do not include a header row. An example file, Example_Output_Profile.csv, has been provided with the sensor data. Note that the example file describes an aircraft, not the lawnmower.

Requirements for Deliverable 2: Report

Your report must be submitted in PDF or Microsoft Word Format and should comprise the following:
1) A brief qualitative description of your method for computing the lawnmower's position, velocity and heading from the sensor data and your reasons for selecting this approach. Include at least one flowchart and references to where the full details of the algorithms may be found (such as course materials, books and papers). Indicate the specific equations you have implemented by stating the equation numbers or powerpoint slide numbers from your references. You can also include reasons for rejecting alternative approaches if you wish.
2) Graphs showing your position, velocity and heading solution. Note that it is clearer to show position relative to your starting point rather than absolute position (make sure you include the start coordinates). You can include additional graphs showing subsystem solutions if you want to.
3) A brief discussion of your results. Do the position, velocity and heading solutions look reasonable for a lawnmower?
4) An appendix comprising your source code, which should be commented. It should be clear from your comments and variable names exactly which algorithms you have implemented. There is no need to reproduce code that has been provided for you on Moodle.

You must ensure that you reference the sources you use to help you with this, such as the lecture slides and notes, workshop material and any other books or papers you use. Failing to reference your sources is a form of plagiarism and will result in lower marks. Cite your sources where you use them in your text with a number in square brackets, e.g. [1]. If you use a source more than once, you must cite it each time. Full details of each reference, including author(s), title, place of publication and date should then be listed at the end of your report. An example follows:

> "[1] P. D. Groves, Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems, 2nd Edition, Artech House, 2013."

There is no word limit or page limit, but it is recommended that you write about 2 pages of text (excluding diagrams, graphs and the code listing)

Submission and Deadline

Both deliverables should be uploaded to Moodle by **16:00 on Tuesday 8 February 2024**. Your report should include your names, student numbers and UCL email addresses, which will be used to send you feedback and a provisional mark. In the event of technical problems with Moodle, email your deliverables to p.groves@ucl.ac.uk (same deadline applies). It is recommended that you double check all files prior to upload; it is the students' responsibility to ensure that their submission is complete prior to the deadline. Please note that .rar files are not permitted (.zip files are OK, though separate files are preferred).

Please note that this exercise is to be completed in groups of three. You are welcome to discuss this with other students, but you must be able to provide evidence that you have completed the task yourself. Suspiciously similar submissions will be investigated.

If you are working as a group, only one of you needs to upload the coursework to Moodle, but you must include the name, student number and UCL email address of all students on the report to ensure that marks are awarded to all of you..

Assessment

The mark scheme is as follows:

- **Solution accuracy: 20%** – Is your solution accurate? How does it compare with the optimal solution? How big is the initialisation error? Does the solution subsequently converge to the truth? The position, velocity and heading will be assessed.
- **Solution design: 40%** – Do you make use of all of the measurements effectively? How do you integrate the measurements from the different sensors? Do you correct or calibrate the sensor errors? How do you handle outliers? Are your algorithms correct?
- **Report quality: 30%** – Is your design clearly described? How well do you explain the motivation? How well do you discuss the results? What is the quality of your graphs? Is your report clearly laid out and well referenced? Are all symbols and acronyms defined and appropriate measurement units used?
- **Code quality: 10%** – Is your code clearly and logically structured with easy-to-follow naming conventions? Is your code clearly and comprehensively commented?

Coursework will be marked and feedback posted to Moodle by 9 March.

Help

We can provide individual help on the workshop exercises. However, we cannot provide individual help on the coursework as all students must be treated equally. Therefore, please post all questions to the coursework discussion forum (on the assessment tab). If you wish to ask a question anonymously, email it to me and I will post the answer on the forum.

Paul Groves 8/1/2024