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Patrik Axelsson and Ylva Jung

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Patrik Axelsson, Ylva Jung

Division of Automatic Control

E-mail: axelsson@isy.liu.se, ylvju@isy.liu.se

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Address:

Department of Electrical Engineering

Linköpings universitet

SE-581 83 Linköping, Sweden

WWW: <http://www.control.isy.liu.se>

AUTOMATIC CONTROL
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Abstract

This project was a part of the course *Applied Control and Sensor Fusion* (<http://www.control.isy.liu.se/student/graduate/AppliedControl/index.html>) during summer and fall 2010. The goal of the course was to be a practical study of implementation issues, not always encountered in the life of a PhD student.

A segway was constructed using a LEGO Mindstorms NXT kit and a gyro, and the goal was to construct a self balancing segway. To do this the motor angles and the gyro measurements were available, and a working Simulink program. The main focus in this project has been to construct an observer.

The segway can be used for demos in basic control courses, and a manual can be found at the end of the report.

Keywords: segway, manual, observer, lego mindstorms

Lego Segway Project Report

Patrik Axelsson – axelsson@isy.liu.se

Ylva Jung – ylvju@isy.liu.se

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1 Introduction

In this project a LEGO segway robot has been built as a part of the course *Applied Control and Sensor Fusion* (<http://www.control.isy.liu.se/student/graduate/AppliedControl/index.html>). The goal of this project course is to be a practical study of implementation issues, not always encountered in the life of a PhD student. A short presentation of the segway can be found in Section 2. The modeling is described in Section 3 and the controller in Section 4.

The initial plan for the project was to construct and implement an H_∞ -controller, and if the project time allowed it, construct and implement an observer. We started out on an H_∞ -controller, but since we did not like the way of implementing an observer by integrating a sensor measurement we soon switched to observer construction instead.

The observer is presented in Section 5 and works well on simulated data, but when trying it on the real segway it did not work at all. To investigate why we tried to log the measured data by connecting the segway to the PC, using Bluetooth and a USB cable, but we did not succeed, see Section 6.

In Section 7 a short user manual can be found, describing how to use the existing programs (for e.g. small demonstrations), and how to develop and compile new programs.

If there had been more time, we had most likely tried to design and implement an EKF and/or proceed to design and implement an H_∞ controller.

2 Segway

The segway used is based on LEGO Mindstorms NXT and assembled according to [1]. All parts are standard LEGO Mindstorms components, except for a single direction gyro sensor from HiTechnic.

The segway is an implementation of an inverted pendulum and is a nonlinear system. The nonlinear model and the linearised model used in this project are further presented in Section 3.

Inputs and outputs

The actuators of the segway are two DC motors, one connected to the left wheel and one to the right. To control these actuators, the controlled input is:

- voltage to the motors recalculated to two PWM signals to the left and right DC motor.

Some of the segway state variables are measured and the outputs from the segway are:

- the DC motor angles θ_{m_l} and θ_{m_r} .

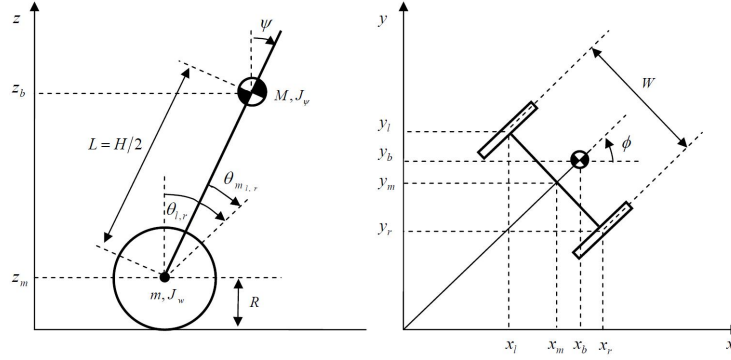


Figure 1: Side view and plane view of the two-wheeled inverted pendulum modeled [1].

Table 1: Physical parameters used in the model.

g	gravitational acceleration
J_m	DC motor moment of inertia
J_w	wheel moment of inertia
J_ϕ	body yaw moment of inertia
J_ψ	body pitch moment of inertia
L	distance of the mass center from the wheel axis
m	wheel weight
M	body weight
n	gear ratio
R	wheel radius
W	body width

- the body pitch angular velocity, $\dot{\psi}$ from the gyro.

The other states, including the body pitch angle ψ , have to be calculated, and therefore an observer will be used in this project.

3 Model

The model used is derived by [1]. Since the segway has been built in the same way as the segway the models were developed for, these are judged to be valid in this project.

Figure 1 shows a simplified two-wheeled inverted pendulum from the side and from the top, with the coordinates used in the report. These are

- θ : average angle of left and right wheel, θ_l and θ_r .
- ψ : body pitch angle
- ϕ : body yaw angle

and some parameters are presented in Table 1 (for the numerical values, see [1]).

Lagrange equation leads to a description of the motion,

$$[(2m + M)R^2 + 2J_w + 2n^2 J_m] \ddot{\theta} + [MLR \cos \psi - 2n^2 J_m] \ddot{\psi} - MLR \dot{\psi}^2 \sin \psi = F_\theta \quad (1)$$

$$[MLR \cos \psi - 2n^2 J_m] \ddot{\theta} + [ML^2 + J_\psi + 2n^2 J_m] \ddot{\psi} - MgL \sin \psi - ML^2 \dot{\phi}^2 \sin \psi \cos \psi = F_\psi \quad (2)$$

$$\left[\frac{1}{2} m W^2 + J_\phi + \frac{W^2}{2R^2} (J_w + n^2 J_m) + ML^2 \sin^2 \psi \right] \ddot{\phi} + 2ML^2 \dot{\psi} \dot{\phi} \sin \psi \cos \psi = F_\phi \quad (3)$$

These equations are nonlinear but can be linearised around a point of equilibrium, in this case the upstanding position of the segway ($\psi \rightarrow 0 \Rightarrow \sin \psi \rightarrow \psi, \cos \psi \rightarrow 1$ and higher order terms are neglected). Equations (1)-(3) can then be approximated as

$$[(2m + M)R^2 + 2J_w + 2n^2 J_m] \ddot{\theta} + [MLR - 2n^2 J_m] \ddot{\psi} = F_\theta \quad (4)$$

$$[MLR - 2n^2 J_m] \ddot{\theta} + [ML^2 + J_\psi + 2n^2 J_m] \ddot{\psi} - MgL \psi = F_\psi \quad (5)$$

$$\left[\frac{1}{2} m W^2 + J_\phi + \frac{W^2}{2R^2} (J_w + n^2 J_m) \right] \ddot{\phi} = F_\phi, \quad (6)$$

where $F_{\theta, \psi, \phi}$ are the forces in the θ, ψ, ϕ directions, respectively.

The connection between θ and ψ and their derivatives is described in Equations (4) and (5), and ϕ in Equation (6). So with the state vectors

$$x_1 = (\theta \quad \psi \quad \dot{\theta} \quad \dot{\psi})^T, \quad x_2 = (\phi \quad \dot{\phi})^T \quad (7)$$

and the expressions for $F_{\theta, \psi, \phi}$ as in [1], the motion equations can be rewritten and divided into two separate state space models,

$$\dot{x}_1 = A_1 x_1 + B_1 u \quad (8)$$

$$\dot{x}_2 = A_2 x_2 + B_2 u \quad (9)$$

where $u = (v_l \quad v_r)^T$ are the left and right motor voltages. In the model in Equation (8), with the equations handling the upright position (no turning possibility needed), $v_l = v_r$, so therefore these are simplified to the one input signal, u , the voltage to the motors. The angles θ and ψ are in radians and the angular velocities $\dot{\theta}$ and $\dot{\psi}$ are in radians/s. Since this project has focused on the control of θ and ψ , only the model described in (8) has been considered.

The nonlinear state equations are linearised around the upstanding position and are thus only valid around that point.

4 Controller

The controller implemented in [1] is a modified linear quadratic controller, with a feedback gain and an integral gain (to help control the position of the segway). The weight matrices are

$$Q_{\text{lqr}} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 6 \cdot 10^5 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 4 \cdot 10^2 \end{pmatrix}, \quad R_{\text{lqr}} = \begin{pmatrix} 1 \cdot 10^3 & 0 \\ 0 & 1 \cdot 10^3 \end{pmatrix} \quad (10)$$

with $x_{\text{lqr}} = (\theta \quad \psi \quad \dot{\theta} \quad \dot{\psi} \quad \int (\theta - \theta_{\text{ref}}))^T$. So the $Q_{\text{lqr}}(2, 2)$ -element is the weight for ψ and the $Q_{\text{lqr}}(5, 5)$ -element is working on an added state, the integrated difference

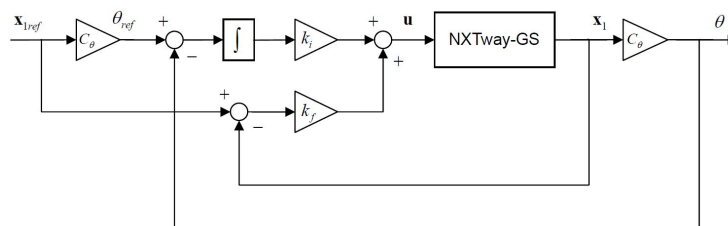


Figure 2: An overview of the modified LQ controller [1]. C_θ denotes the conversion from x_1 to θ .

between the angle θ and the reference θ_{ref} , see Figure 2 for the Simulink block diagram of the controller.

The controller has not been evaluated or improved in this project.

5 Observer

The observer that was implemented in [1] integrated the measured angular velocity from the gyro. One thing that you learn in a basic course in signal processing is that the measured signal from many sensors are noisy and influenced with drift. That is, a constant sensor error will grow without limits, when integrating the signal. Integrating this signal directly will therefore be a bad decision. Instead we developed a model based observer to cope with this problem. The segway is a nonlinear system, that means, a nonlinear observer should be used, e.g. Extended Kalman Filter (EKF). Since we used a linearised model of the segway in upstanding position, as described in Section 3, a stationary Kalman Filter (KF) was used. The system can be described by a continuous state space model according to (8),

$$\dot{x}_1 = Ax_1 + Bu, \quad (11)$$

where $x_1 = (\theta \ \psi \ \dot{\theta} \ \dot{\psi})^T$, A and B are system matrices and u is the voltage to the motors, see Section 3 and [1] for more details.

5.1 Design

We augmented this model with one more state δ in order to take the drift of the gyro into consideration. The new model, where we also have included a noise model, can be written

$$\dot{x} = \underbrace{\begin{pmatrix} A & 0 \\ 0 & 0 \end{pmatrix}}_{\bar{A}} x + \underbrace{\begin{pmatrix} B \\ 0 \end{pmatrix}}_{\bar{B}} u + \underbrace{\begin{pmatrix} B & 0 \\ 0 & 1 \end{pmatrix}}_{\bar{G}} w, \quad (12)$$

where $x = (\theta \ \psi \ \dot{\theta} \ \dot{\psi} \ \delta)^T$ is the augmented state vector and $w = (w_1 \ w_2)^T$ is the noise vector.

The measured signals are the angular velocity of the body from the gyro and the motor position of the two motors. First, we model the measured angular velocity as

$$y_1 = \dot{\psi} + \delta = \begin{pmatrix} 0 & 0 & 0 & 1 & 1 \end{pmatrix} x. \quad (13)$$

It is a bit more tricky to find a relationship between the measured motor angles and

the states. A glance at the existing solution gave us

$$\begin{aligned}\theta &= \frac{1}{2}(\theta_l + \theta_r) = \frac{1}{2}(\theta_{m,l} + \psi + \theta_{m,r} + \psi) = \\ &= \frac{1}{2}(\theta_{m,l} + \theta_{m,r}) + \psi = \theta_m + \psi,\end{aligned}\quad (14)$$

where θ_l and θ_r are the angles of the left and right wheel, $\theta_{m,l}$ and $\theta_{m,r}$ are the angles of the left and right motor, which are measured, and $\theta_m \triangleq \frac{1}{2}(\theta_{m,l} + \theta_{m,r})$. The second measurement equation can be written

$$y_2 = \theta_m = (1 \quad -1 \quad 0 \quad 0 \quad 0) x, \quad (15)$$

and the complete measurement equation with measurement noise added is at last obtained as

$$y = \begin{pmatrix} 0 & 0 & 0 & 1 & 1 \\ 1 & -1 & 0 & 0 & 0 \end{pmatrix} x + e = \bar{C}x + e. \quad (16)$$

Simple calculations show that the model is observable, i.e., the observability matrix \mathcal{O} has full rank.

The stationary KF can be written as

$$\dot{\hat{x}} = (\bar{A} - K\bar{C})\hat{x} + (\bar{B} \quad K) \begin{pmatrix} u \\ y \end{pmatrix}, \quad (17a)$$

$$\bar{A}P + P\bar{A}^T - P\bar{C}^T R^{-1} \bar{C}P + \bar{G}Q\bar{G}^T = 0, \quad (17b)$$

$$K = P\bar{C}^T R^{-1}, \quad (17c)$$

where $R = E[ee^T]$ and $Q = E[ww^T]$. We have also assumed that the cross correlation between the process noise w and the measurement noise e is zero. The MATLAB function *lqe* has been used to calculate the observer gain K . The covariance matrices for the process noise and measurement noise are chosen as

$$Q = \begin{pmatrix} 20 & 0 \\ 0 & 0.1 \end{pmatrix} \quad (18a)$$

$$R = \begin{pmatrix} 0.01 & 0 \\ 0 & 0.001 \end{pmatrix}. \quad (18b)$$

5.2 Implementation

The observer has to be discretised before it can be implemented in the Simulink diagram. The discretisation is made with zero order hold, that is

$$x_{k+1} = A_d x_k + B_d u_k, \quad (19a)$$

$$y_k = C_d x, \quad (19b)$$

where

$$A_d = e^{\bar{A}T_s}, \quad (20a)$$

$$B_d = \int_0^{T_s} e^{\bar{A}t} \bar{B} dt, \quad (20b)$$

$$C_d = \bar{C}. \quad (20c)$$

The sample time T_s is 4 ms.

The measured gyro data are in degrees/s but they are given with an offset. An estimate of the offset is obtained if the measured data is averaged over several readings while the segway is standing still. This is done during the initialisation task in the Simulink diagram. The offset is then subtracted from the measurement before it enters the observer. A transformation from degrees/s to rad/s also has to be done both for the gyro data (after the offset is removed) and for the measured motor angles.

5.3 Result

The linearised model was simulated with our observer. Figure 3 shows the estimated θ , ψ , $\dot{\theta}$ and $\dot{\psi}$. Note that the estimation starts after 1 s because the first second is used to perform the initialisation task. We can see that the estimated states follow the true states well.

There are some differences in the beginning of the second state but it is less than 5° which we thought would be sufficient. These differences probably stem from the peak in the fifth state, δ , causing a discrepancy between the true and estimated $\dot{\psi}$, thus leading to an error in the ψ state. We have also compared our estimates with the estimates from the existing observer in [1] and they are more or less the same. The state δ , that describes the drift in the gyro, is shown in Figure 4.

The controller is obviously able to hold the segway in an upstanding position with our observer during the simulation. But when we download the observer to the real segway and run it, the segway can not be controlled to an upstanding position. We therefore tried to save the estimates from our observer and the existing one to see how different they are on the segway, see Section 6.

The different behaviour of the segway in simulation vs. reality is probably because of the linearisation made in Section 3; the model and controller are linear but the reality is nonlinear. One way to better imitate this situation would be to implement the nonlinear system in the simulation model, to be able to tune the Q , R matrices in eq. (18) in a more suitable way. Another solution would be to use a time varying Kalman filter instead of the time invariant KF we have used.

6 Data logging

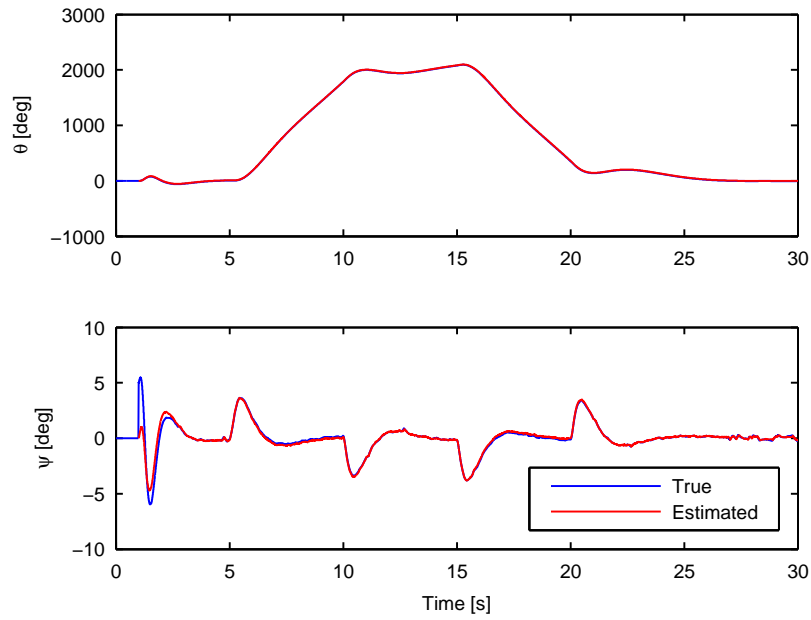
The obtained observer works very well during simulations, but not when compiled and used on the segway. Therefore we wanted to log the measured data from the segway to better see what happens and why this did not work. Our intention was to see how to tune the observer to the real segway, i.e., choose new Q and R matrices that fit the true system better.

It is possible to connect the LEGO NXT brick to a computer using either Bluetooth or a USB cable, and we started using the Bluetooth connection since this means the segway can move around freely, like it is supposed to. But we could not get the connection to work, the COM port did not register anything being sent or recieved. To use the USB connection an additional program, USBlib, had to be downloaded that did not agree with the firmware version used. We changed back to an older version of the firmware, but this took away the possibility to compile and download new programs to the segway, and we decided not to proceed with this.

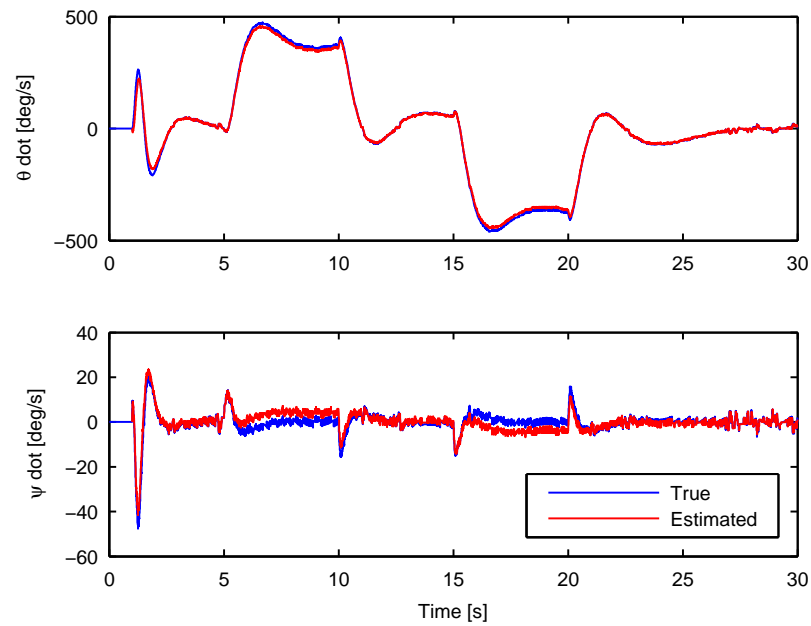
So sadly enough we did not succeed in logging data, which makes it hard to tell what the problem with our observer was.

7 User Manual

This section describes how to build the Simulink diagram and download the program to the segway. A description of how to use the segway is also included. There is also



(a) State one and two.



(b) State three and four.

Figure 3: The true states (blue) and the estimated states (red) with our observer.

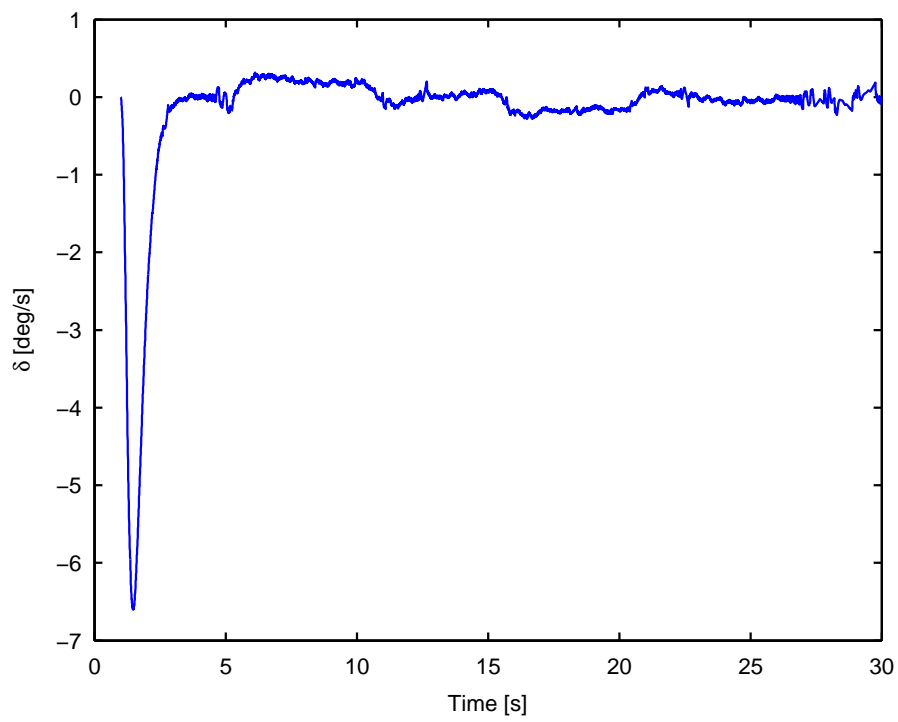


Figure 4: The estimated offset of the gyro, i.e., state five.

another MATLAB toolbox available at [3] which is good if you only want to test the sensors. No instructions for the second toolbox are presented in this report.

7.1 How to use NXTway-GS

The given controller in [1] uses the MATLAB toolbox *Embedded Coder Robot for LEGO Mindstorms NXT* or for short *ECRobot NXT*. Information about the toolbox and how to install can be found in [2].

All the files for [1] can be found on the desktop of the computer RLLT-12 in the directory *Segway filer*. The MATLAB files can then be found under *nxtway_gs\models*. The file *nxtway_gs.mdl* is a simulation model that uses the controller in *nxtway_gs_controller.mdl*. The rest of this section focus on *nxtway_gs_controller.mdl* since it is this file that is used on the segway.

The main window of the file *nxtway_gs_controller.mdl* can be seen in Figure 5. The controller is implemented in the subsystem *nxtway_app*. Press the button *Generate code and build the generated code* to do what it says. However, there is some problem with the installation so the only thing that happens is that the Simulink diagram is built. The rest has to be done manually according to

- Open *C:\cygwin\bin\bash.exe*
- Go to the directory *c:\Document and Settings\rtadm\Desktop\Segway filer\nxtway_gs\models\nxtprj*
- Write *make all*
- Write *make rxeflash*
- Connect and start the segway
- Write *sh ./rxeflash.sh*

The program is now on the robot and is called *nxtway_app* which is the same as the Simulink subsystem described above.

7.2 Start the Robot

The main things to know about the robot is:

1. Press the orange button to start the robot.
2. Walk through the menus with the triangular buttons.
3. Confirm with the orange button.
4. Go back with the dark gray button.

The program that is downloaded in Section 7.1 is started according to:

1. Press the orange button to start the robot.
2. Use the triangular and the orange buttons to choose *My Files/Software files/nxtway_app*.
3. Choose the alternative called *run* and confirm with the orange button.
4. The main menu for the NXT program is now visible. The display shows how to continue.
5. The robot must be held still in an upright position when the start button (right triangular button) is pressed. Release the robot when a beep sounds.

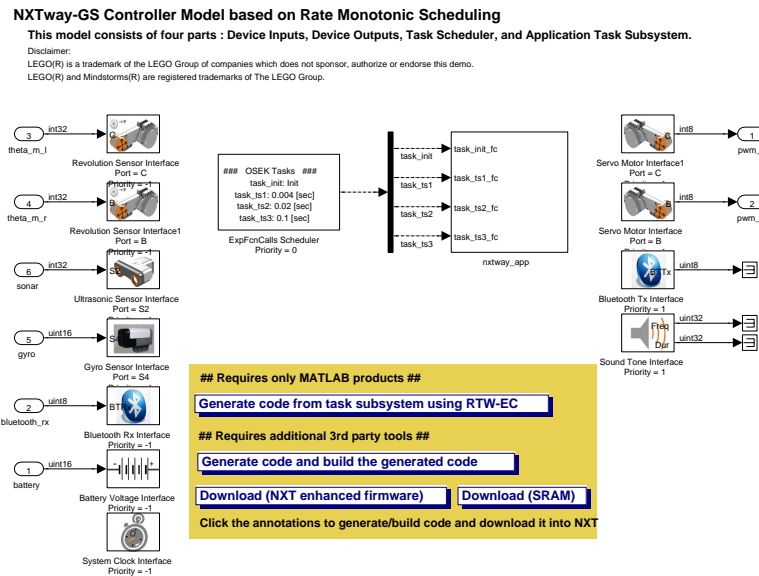


Figure 5: The main window of the file *nxtway_gs_controller.mdl*. The controller is implemented in the subsystem *nxtway_app*.

7.3 Develop new Programs

This section describes how you can develop your own program in ERobot NXT. It is best to start with *nxtway_gs_controller.mdl* since all the necessary settings are correct in that file. Save the file as something new, e.g. *my_terminator*, and you are ready to develop. Start by renaming the subsystem *nxtway_app* to a name of your choice, e.g. *terminator*. Then, right click on the button *Generate code and build the generated code*, choose *Annotation Properties...* Finally, change the name of the system you want to build in the *ClickFcn* text editor. In other words, change from `nxtbuild('nxtway_app', 'build')` to `nxtbuild('terminator', 'build')`. You are now free to implement your on program. The program should be implemented in the subsystem you just renamed, i.e., *terminator*.

7.4 Possible Error Messages.

You can find the solutions of some errors that may occur in this section.

- If

```
Error executing callback 'ClickFcn'
Error using ==> nxtbuild at 149
### Failed to create nxtprj directory for model: nxtway_app
```

arises when you press the button *Generate code and build the generated code*, then it is probably because you are in the `nxtprj` folder with Cygwin. Go back one folder and try again.

- If you do not get the message `filename.rxe=xxxxx` when you type `sh ./rxe-flash.sh` in Cygwin, there might not be enough space on the NXT. Delete pro-

grams not used and try again. It can also be that you have forgot to turn the robot on.


- If you get an error message saying

```
### Model failed to compile with strict bus check on
### Turning strict bus check off
...
Model has compile errors.
```

when you have pressed the button *Generate code and build the generated code*, then open the file *rtwbuild*. Set a breakpoint at row 201 and then press the button *Generate code and build the generated code* again. MATLAB will now stop at row 201 in *rtwbuild* and you have access to the variable *newExc*. The variable is a MException object and contains information about the error. The error message you are looking for can be found if you dig into the causes, e.g. `newExc.causes{1,1}.causes{1.1}.message`.

References

- [1] Yorihiisa Yamamoto. NXTway-GS (Self-Balancing Two-Wheeled Robot) Controller Design. <http://www.mathworks.com/matlabcentral/fileexchange/19147>
- [2] Takashi Chikamasa. Embedded Coder Robot NXT. <http://www.mathworks.com/matlabcentral/fileexchange/13399>
- [3] MATLAB for LEGO MINDSTORMS Robots. <http://www.mathworks.com/academia/lego-mindstorms-nxt-software/legomindstorms-matlab.html>

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