Control implementations on the HIGHWIND carousel

Ernesto Denicia

HIGHWIND Scientific Advisory Board (SAB) Meeting
Department of Microsystems Engineering - IMTEK
University of Freiburg, Germany

Agenda: Treating in this talk

- System identification of the carousel

- Model
- Parameter estimation

- State estimator simulations and implementation

- Discrete Linear Quadratic Estimator (DLQE)
- Disturbance state augmented DLQE (steady state Kalman Filter)

- Control simulations and implementation

- Discrete Linear Quadratic Regulator (DLQR)
- Disturbance state augmented DLQR
- Discrete Linear Quadratic Gaussian Control (DLQG)

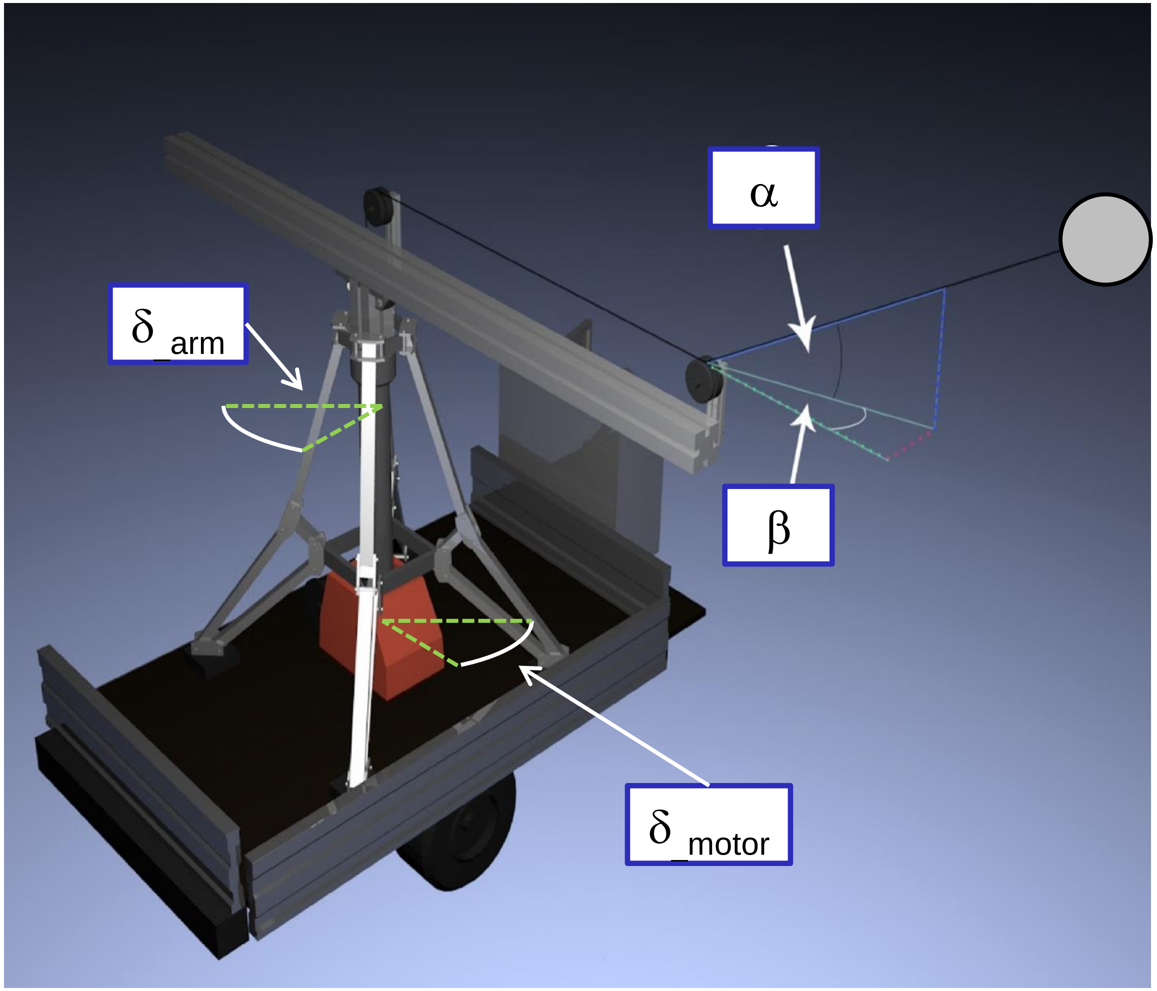
Remarks on this talk

Colors used:

- Real sensor measurements
- Numerical simulations
- References or setpoints
- Estimate simulations (DLQE, augmented DLQE, DLQG)
- Real estimator output (Implemented estimators)
- Experimental control signal (DLQR, augmented DLQR, DLQG)

For angle measurement, radians are prefered to degrees

1.0 System identification of the carousel: Actual model



Actual model considers:

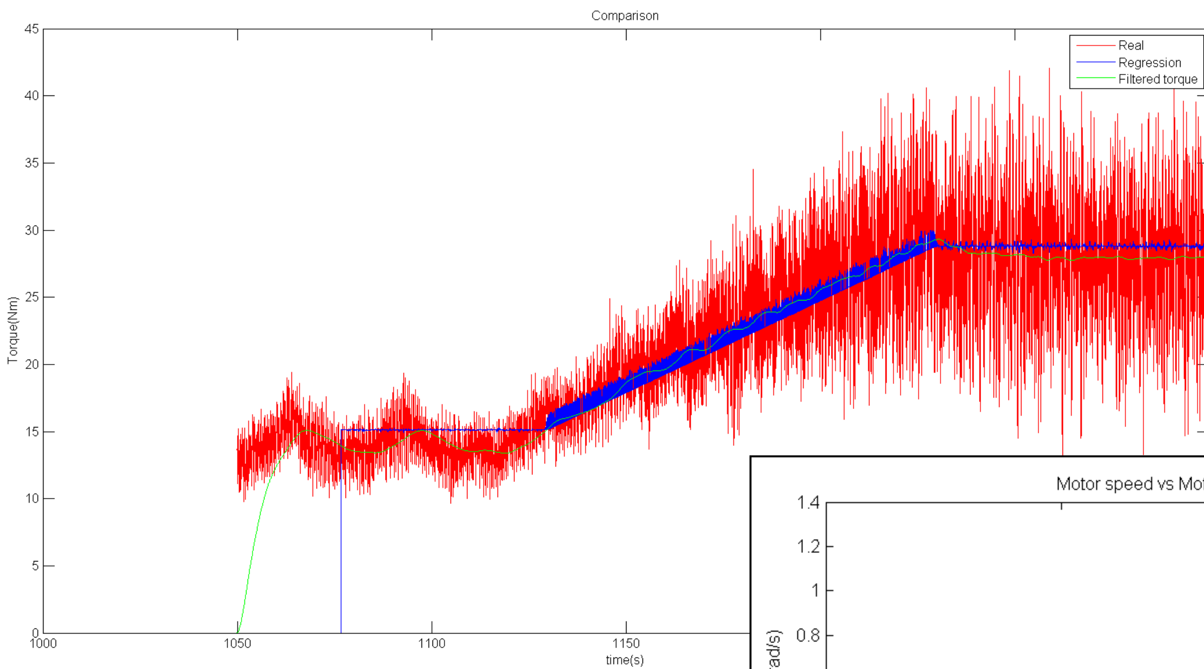
- Kinetic energy:
  - Arm inertia
  - Ball velocity
  - LAS inertia
  - LAS Attachment inertia (tether+ball)
- Potential energy
  - Ball
- Generalized torques
  - Air friction
  - LAS α friction
  - LAS β friction

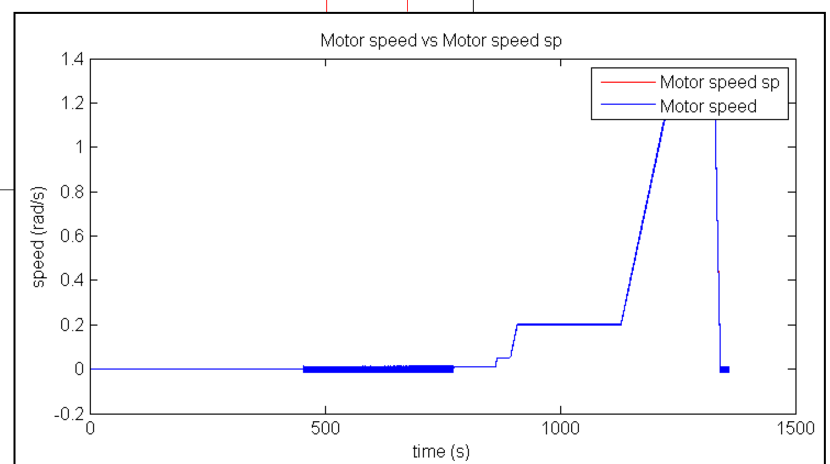
1.1 Entirely physical model

Good torque prediction

$$T = I\alpha + c\omega_{motor}$$

$$\delta_{motor}$$
$$\delta_{arm}$$
$$\alpha$$
$$\beta$$
$$\dot{\delta}_{motor}$$
$$\dot{\delta}_{arm}$$
$$\dot{\alpha}$$
$$\dot{\beta}$$



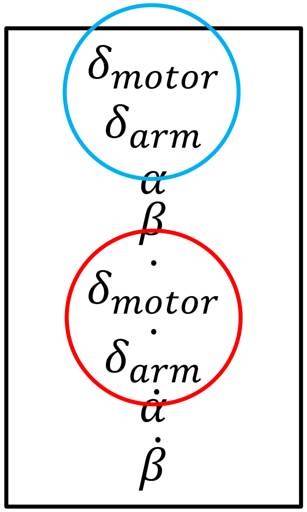


lsq_inertia_friction_filter()

1.2 Physical model detailed

Advantages:

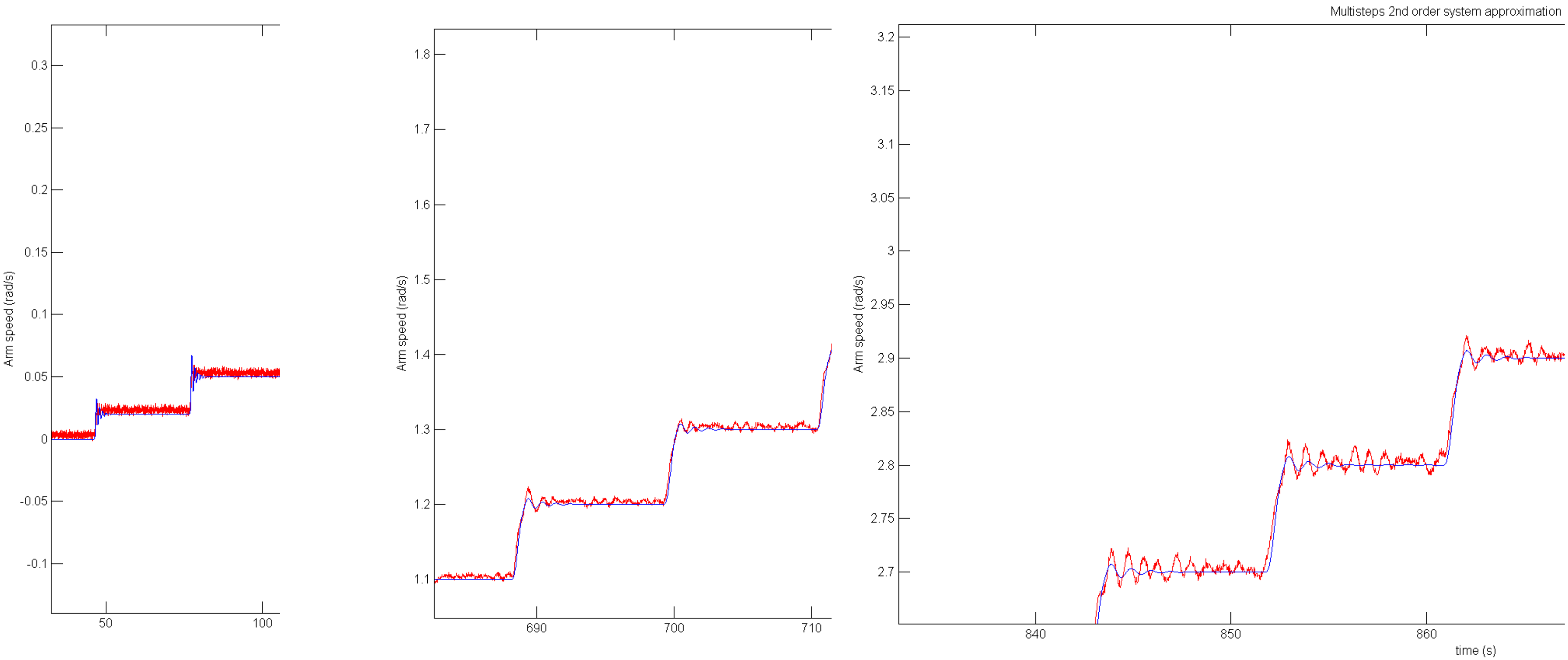
- Differentiate between motor and arm state
- Six first states already being measured and reported



Disadvantages

- Coupling between motor speed and arm speed difficult to measure (rubber band)
- Input: Motor speed setpoint. Motor speed already modified by lower level controllers, algorithm difficult to estimate

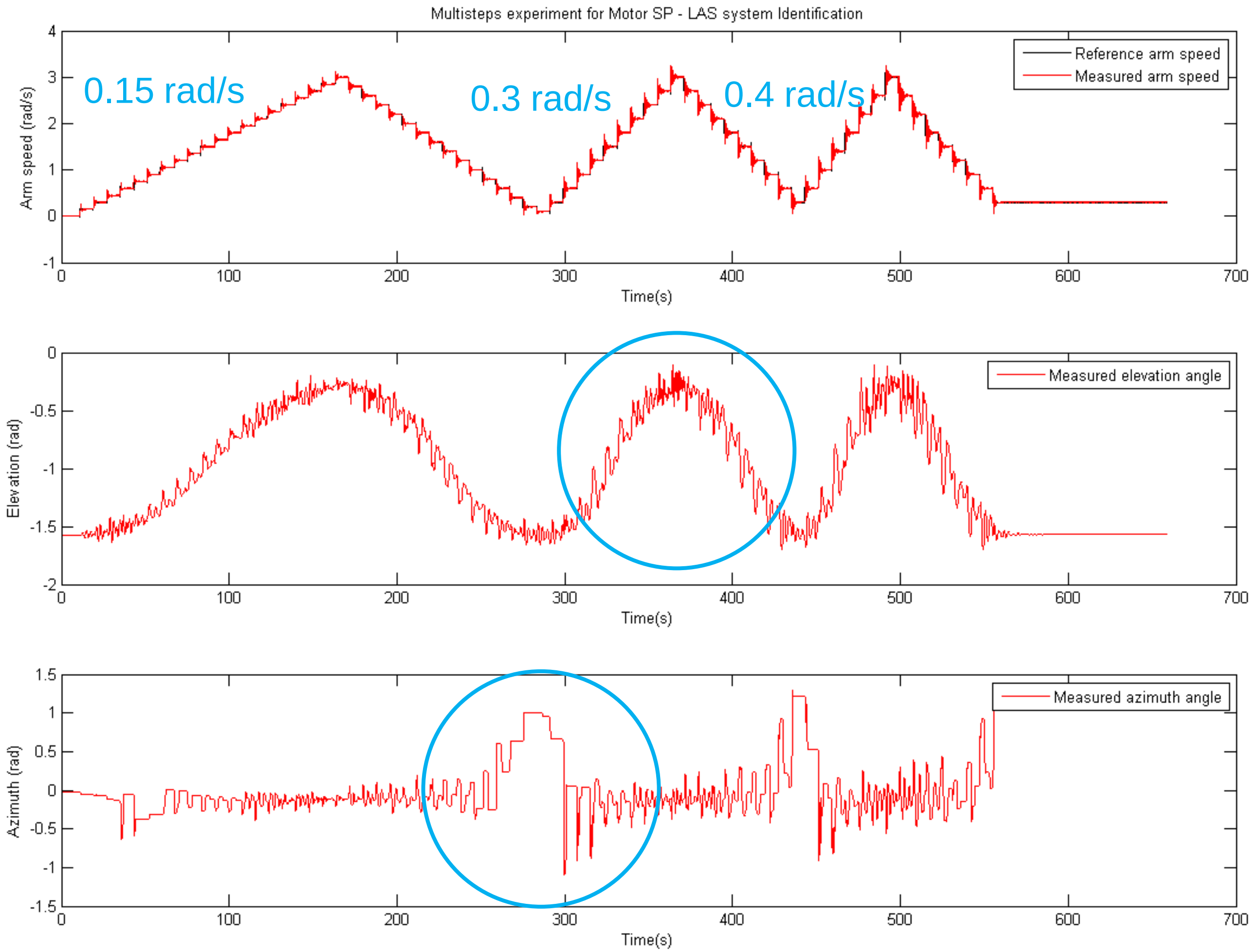
2.1 Idea: $\dot{\delta}_{motor\_sp} \rightarrow \dot{\delta}_{arm}$ as second order system



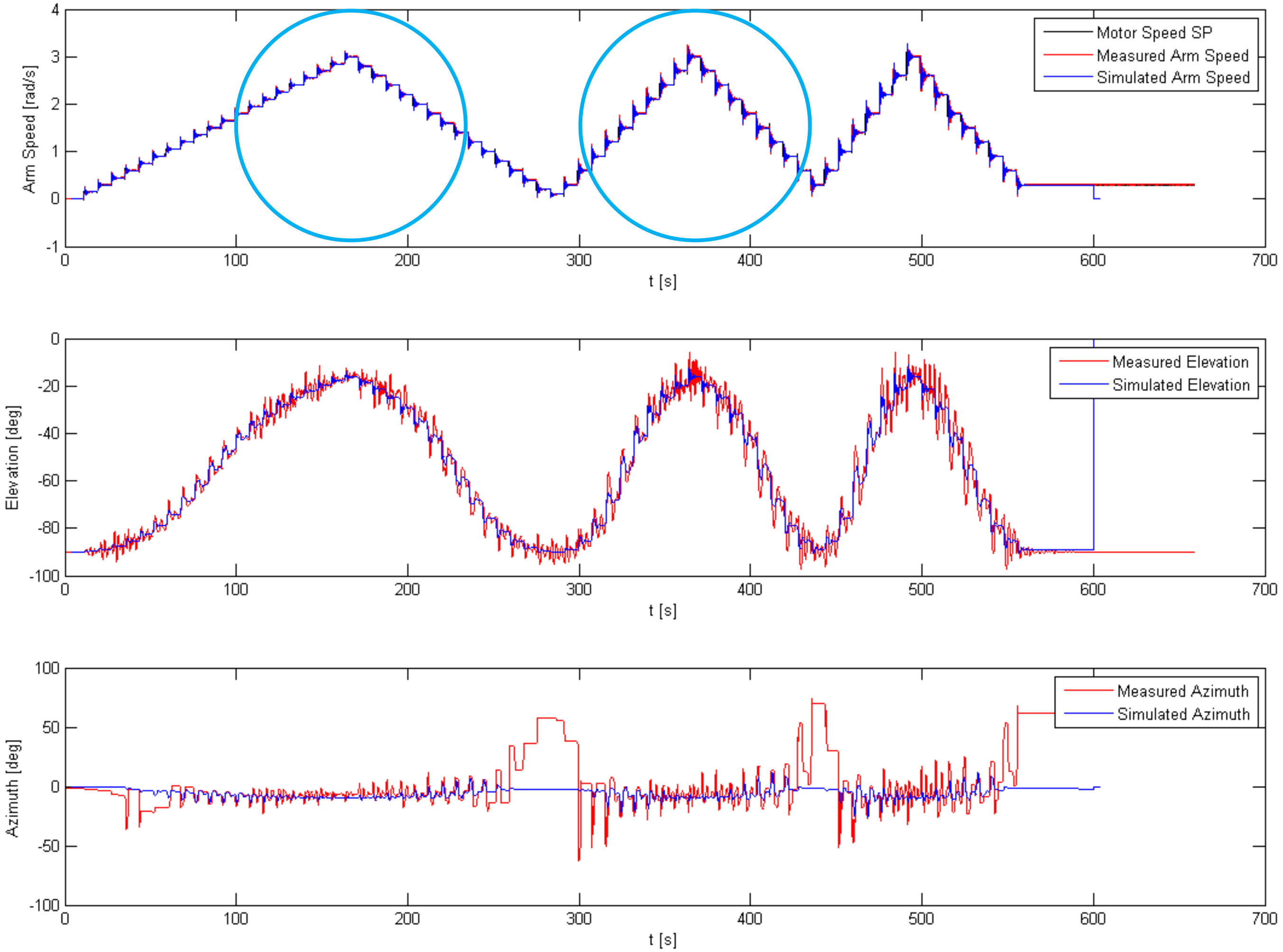
----- Real arm speed ----- Simulated arm speed

3.1 LAS Identification

Multi-steps experiment (avoidance of low speeds)

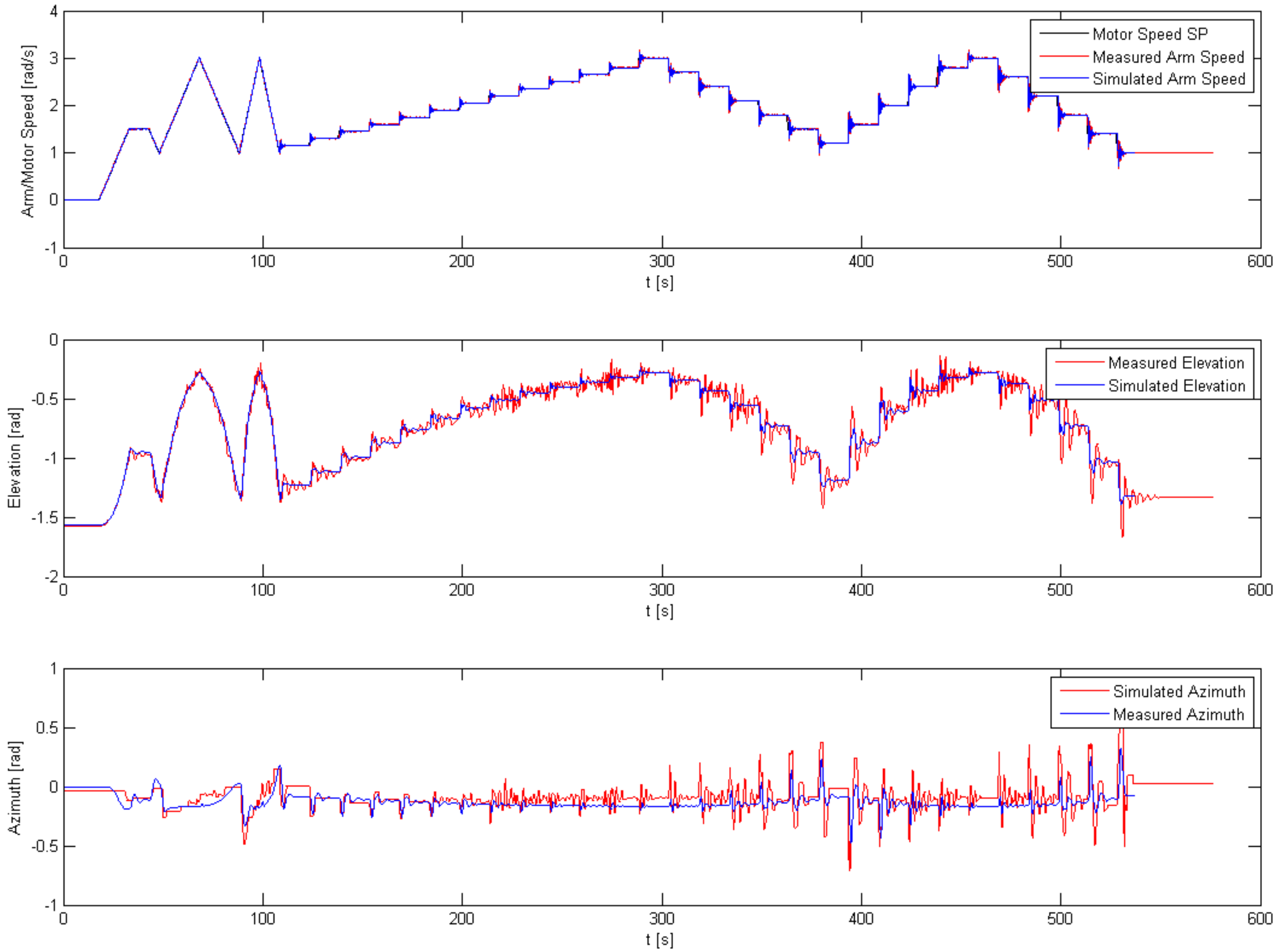


3.2 LAS Identification - Simulation



siemens_step_response_experiment ()

3.3 LAS Identification – Acceptable working range

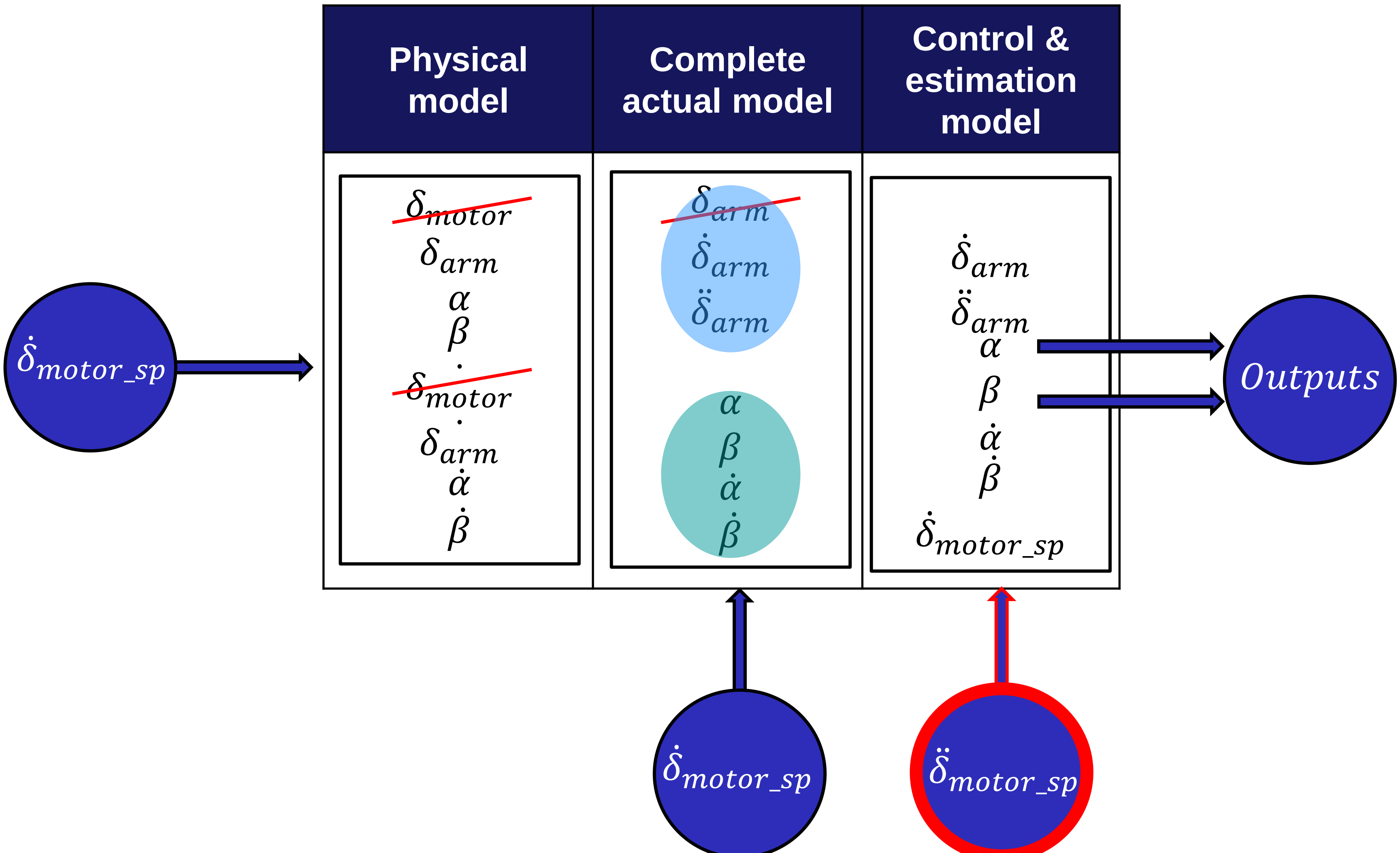


final_step_response_experiment ()

3.4 LAS model parameters

Description	Symbol	Conf. Int.	Covariance matrix
Air-Ball friction	μ_{air}	0.0069 kg/m	1.0e-03 * $\begin{matrix} 0.000002 & -0.000002 & -0.000011 & -0.000006 \\ -0.000002 & 0.062871 & 0.009529 & -0.009383 \\ -0.000011 & 0.009529 & 0.176314 & -0.007819 \\ -0.000006 & -0.009383 & -0.007819 & 0.007186 \end{matrix}$
Elevation LAS friction	$\mu_{\alpha,LAS}$	1.4351 Nms/rad	
Azimuth LAS friction	$\mu_{\beta,LAS}$	0.6122 Nms/rad	
Constant attached inertia	$I_{attached\_LAS}$	0.2853 kg/m^2	

3.5 Model adaptation



4.1 Discrete Linear Quadratic Estimator (DLQE) design

$$\min_{x_0 \dots x_k} \left\| x_0 - \hat{x}_0 \right\|_{P_0}^2 + \left\| x_k - \hat{x}_k \right\|_W^2 + \left\| y_k - \hat{y}_k \right\|_V^2$$

$$s.t. \quad \begin{aligned} x_{k+1} &= \mathrm{A}\mathrm{x}_\mathrm{k} + \mathrm{B}\mathrm{u}_\mathrm{k} + \mathrm{G}\mathrm{w}_\mathrm{k} \\ \mathrm{y}_\mathrm{k} &= \mathrm{C}\mathrm{x}_\mathrm{k} + \mathrm{D}\mathrm{u}_\mathrm{k} + \mathrm{v}_\mathrm{k} \end{aligned}$$

- Linearization at $x_{ss} = [1.5878 \quad -0.8802 \quad -0.0687 \quad 0 \quad 0 \quad 0 \quad 1.5878]$
- Discretization with $\Delta_t = 100ms$ and initial estimate $\overline{x_0} = x_{ss}$

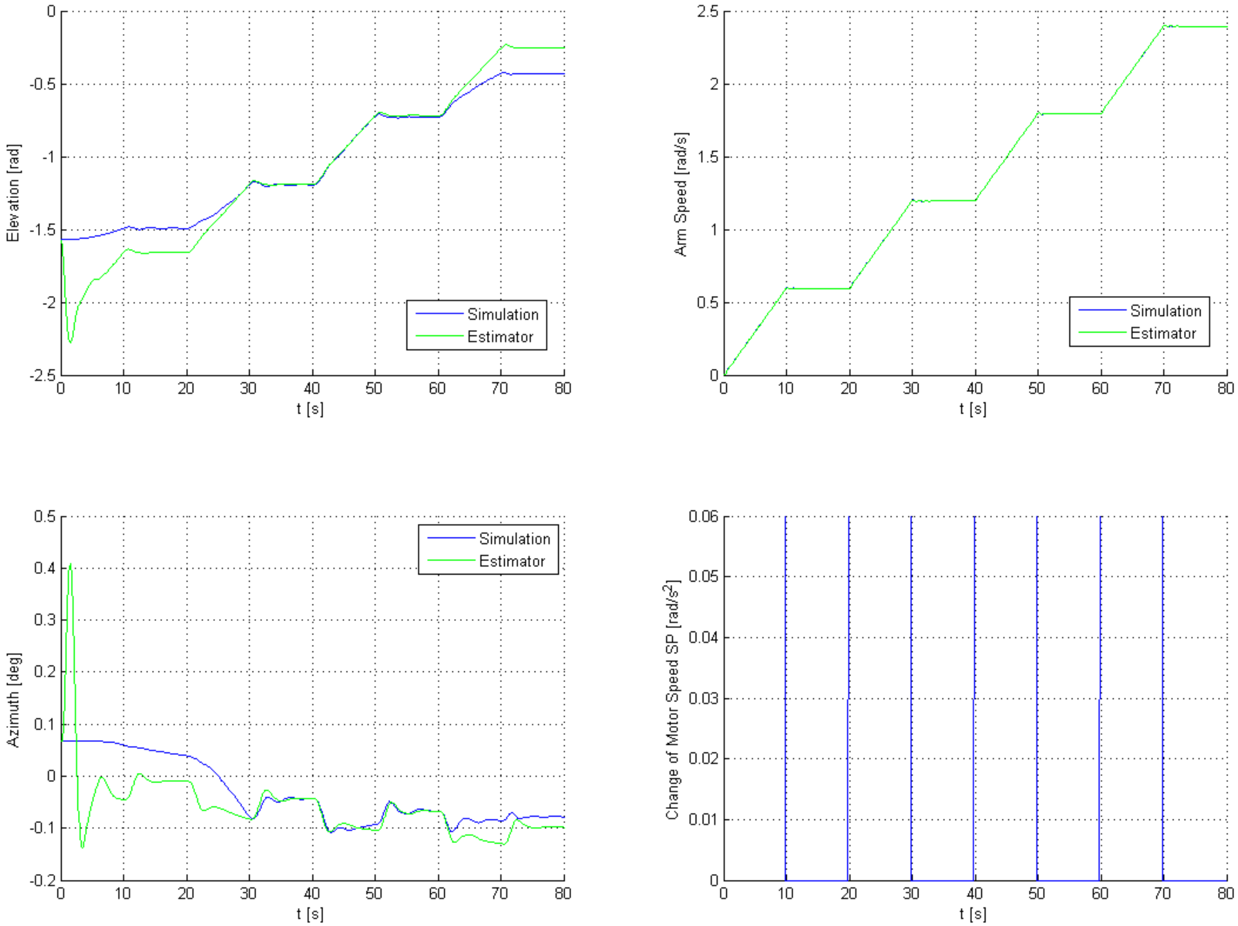
$$x = \begin{bmatrix} \dot{\delta}_{arm} \\ \ddot{\delta}_{arm} \\ \alpha \\ \beta \\ \dot{\alpha} \\ \dot{\beta} \\ \dot{\delta}_{motor\_sp} \end{bmatrix} \quad Q_E = \begin{bmatrix} {w_n}^2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & {w_n}^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & {w_o}^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & {w_o}^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & {w_n}^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & {w_n}^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad R_E = \begin{bmatrix} {v_n}^2 & 0 \\ 0 & {v_n}^2 \end{bmatrix} \quad G = I_{n_x \times n_x}$$

$$v = 0.01$$

$$w_n = 0.001$$

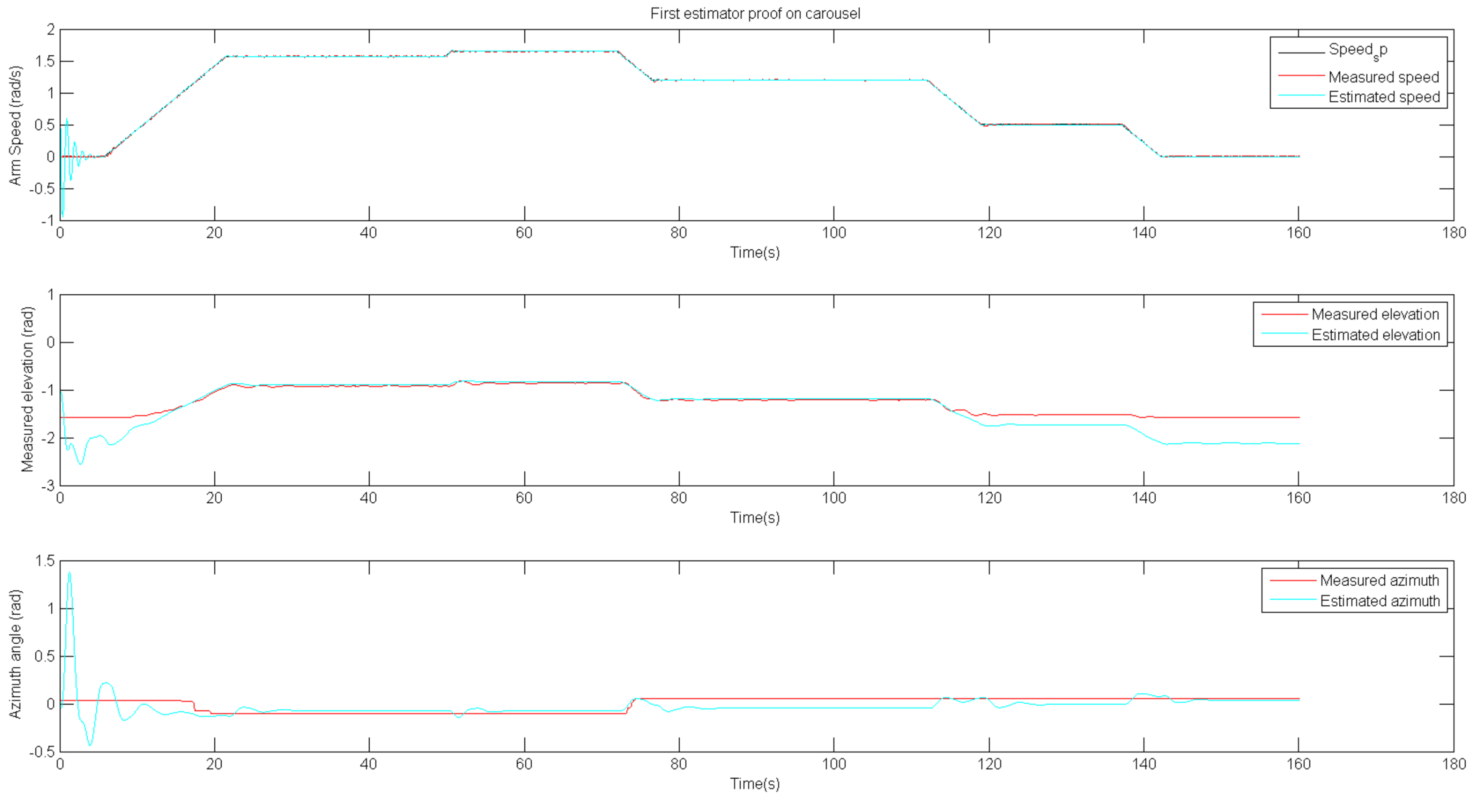
$$w_o = 1 \times 10^{-6}$$

4.2 DLQE Simulation



estimator_simulation()

4.3 DLQE: Experimental Results



kalman1()

4.4 Disturbance state augmented DLQE design

Staying at the linearization setpoint is unlikely for such a setup (tether length varied constantly)

- Mismodelling in elevation angle corrected by the use of an added diturbance state

$$\alpha = \ddot{\cdots} + S_p$$

$$\dot{S}p = -\frac{S_p}{\tau} + w_{n_s}\ with\ w_{n_s} \sim N(0, \Sigma(\ ))$$

- Design characteristics: $\tau = 100$ and $w_{ns} = 0.001$

4.5 Model changes due to augmentation

Physical model	Complete actual model	Control & estimation model	Augmentated control model
~~δ_{motor}~~ δ_{arm} α β ~~$\dot{\delta}_{motor}$~~ $\dot{\delta}_{arm}$ $\dot{\alpha}$ $\dot{\beta}$	~~δ_{arm}~~ $\dot{\delta}_{arm}$ $\ddot{\delta}_{arm}$ α β $\dot{\alpha}$ $\dot{\beta}$	$\dot{\delta}_{arm}$ $\ddot{\delta}_{arm}$ α β $\dot{\alpha}$ $\dot{\beta}$ $\dot{\delta}_{motor\_sp}$	$\dot{\delta}_{arm}$ $\ddot{\delta}_{arm}$ α β $\dot{\alpha}$ $\dot{\beta}$ $\dot{\delta}_{motor\_sp}$ S_p

4.6 Augmented DLQE: initial tuning

- Linearization at $x_{ss} = [1.6196 \quad -0.8802 \quad -0.0696 \quad 0 \quad 0 \quad 0 \quad 1.6196]$
- Discretization with $\Delta_t = 20ms$ and initial estimate $\overline{x_0} = x_{ss}$

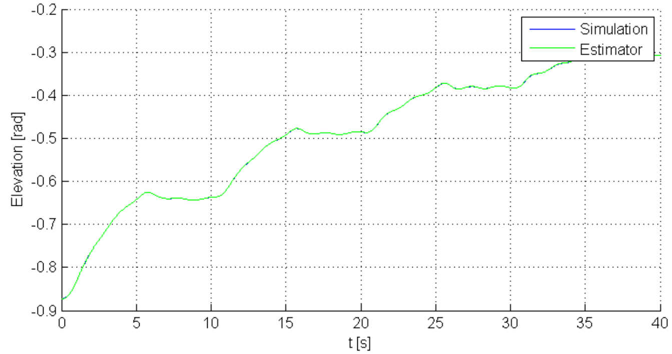
$$x = \begin{bmatrix} \dot{\delta}_{arm} \\ \ddot{\delta}_{arm} \\ \alpha \\ \beta \\ \dot{\alpha} \\ \dot{\beta} \\ \dot{\delta}_{motor\_sp} \\ s_p \end{bmatrix} \quad Q_E = \begin{bmatrix} {w_n}^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & {w_n}^2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & {w_o}^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & {w_o}^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & {w_n}^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & {w_n}^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & w_s \end{bmatrix} \quad R_E = \begin{bmatrix} v_n & 0 \\ 0 & v_n \end{bmatrix} \quad G = I_{n_x \times n_x}$$

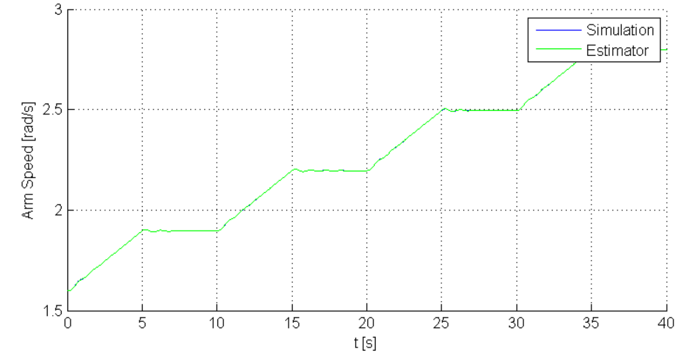
$$v = 0.002$$

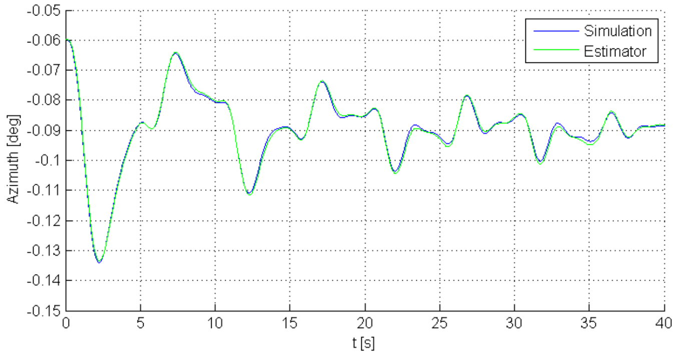
$$w_n = 0.001$$
$$w_o = 1 \times 10^{-6}$$
$$w_s = 0.01$$

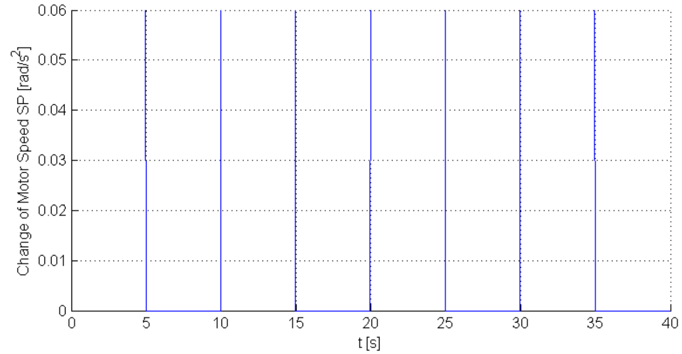
4.7 DLQE Simulation

*Experiment and fine tuning to be seen during the visit









estimator_simulation()

5.1Discrete Linear Quadratic Regulator (DLQR) design

$$\min_{x_0 \ldots x_N \ldots u_0 \ldots u_{N-1}} \|x_N\|_{P_N}^2 + \|x_k\|_Q^2 + \|u_k\|_R^2$$

$$x_{k+1} = \mathrm{A}\mathrm{x}_\mathrm{k} + \mathrm{B}\mathrm{u}_\mathrm{k}$$

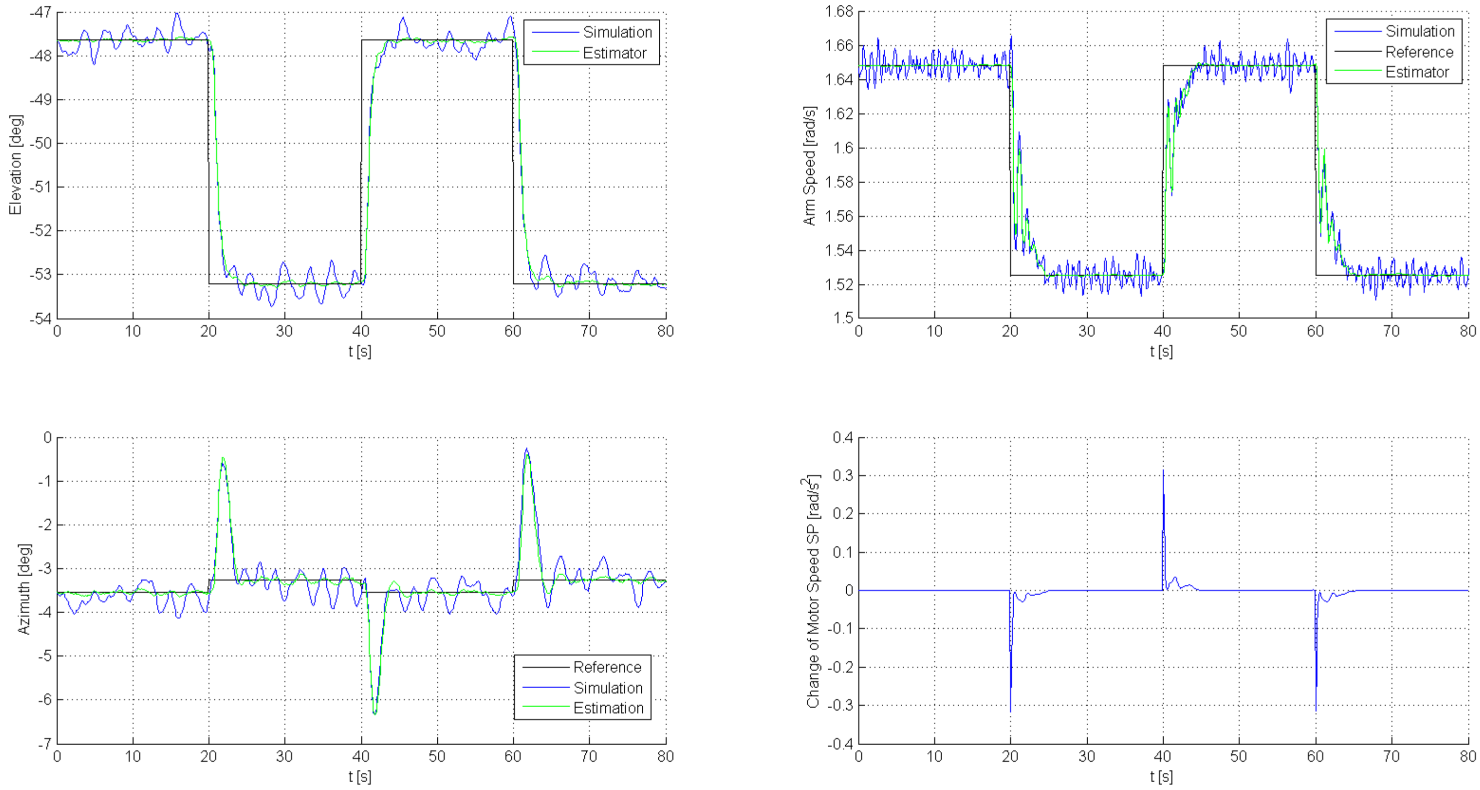
$$s.t. \qquad x_o - \overline{x_o} = 0$$

- Linearization at $x_{ss} = [1.5878 \quad -0.8802 \quad -0.0687 \quad 0 \quad 0 \quad 0 \quad 1.5878]$
- Discretization with $\Delta_t = 100ms$ and initial estimate $\overline{x_0} = x_{ss}$

$$x = \begin{bmatrix} \dot{\delta}_{arm} \\ \ddot{\delta}_{arm} \\ \alpha \\ \beta \\ \dot{\alpha} \\ \dot{\beta} \\ \dot{\delta}_{motor\_sp} \end{bmatrix} \qquad Q = \begin{bmatrix} {q_0}^2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & {q_0}^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 8^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & {q_o}^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 5^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & {q_0}^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & q_0 \end{bmatrix} \qquad R = [2^2] \qquad P_N = [0]$$

$$q_o = 1 \times 10^{-6}$$

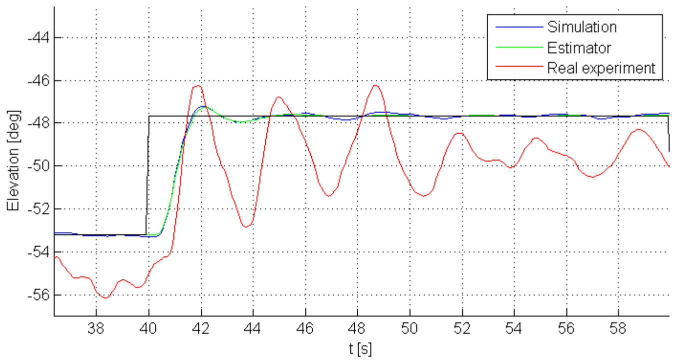
5.2 Discrete Linear Quadratic Regulator (DLQR) simulation

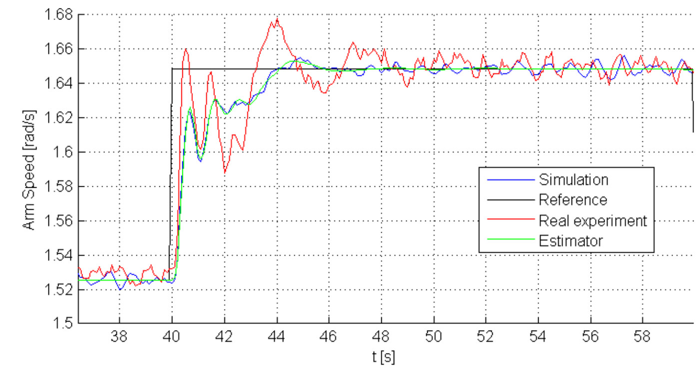


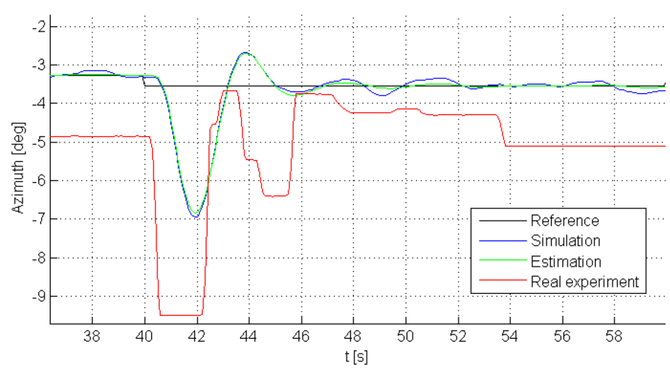
dlqr/carousel_dynamics()

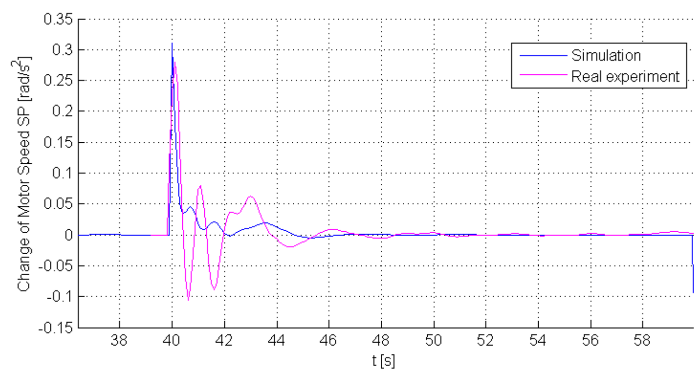
5.3 DLQR experimental results

First attempt









5.4 Disturbance state augmented DLQR design

- Linearization at $x_{ss} = [1.6196 \quad -0.8802 \quad -0.0696 \quad 0 \quad 0 \quad 0 \quad 1.6196]$
- Discretization with $\Delta_t = 20ms$

$$x = \begin{bmatrix} \dot{\delta}_{arm} \\ \ddot{\delta}_{arm} \\ \alpha \\ \beta \\ \dot{\alpha} \\ \dot{\beta} \\ \dot{\delta}_{motor\_sp} \\ s_p \end{bmatrix}$$

$$Q = \begin{bmatrix} {q_0}^2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & {q_0}^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 10^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 7^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 5^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & q_0 \end{bmatrix}$$

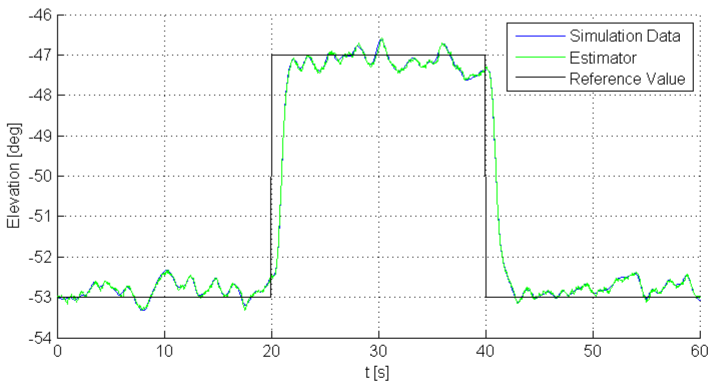
$$q_o = 1 \times 10^{-6}$$

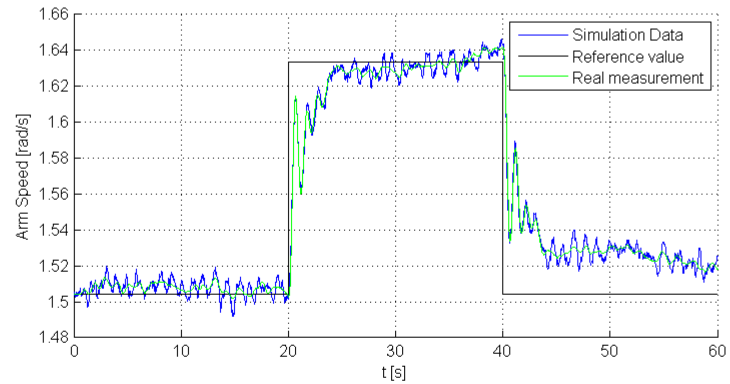
$$R = [5^2]$$

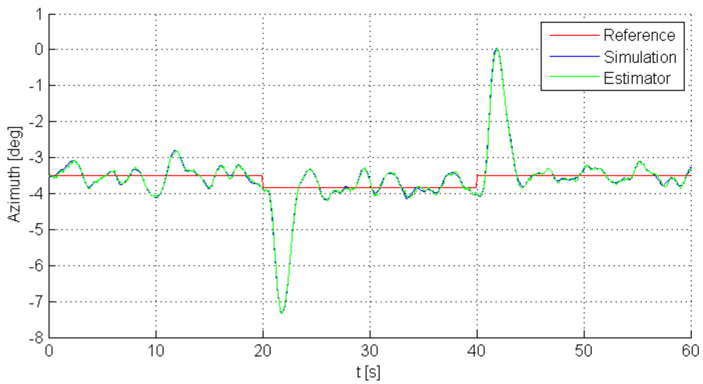
$$P_N = [0]$$

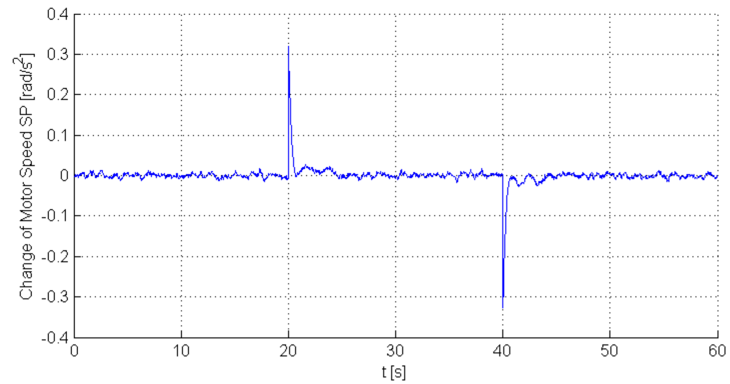
5.5 Disturbance state augmented DLQR simulation

*Experimental results to be seen during the visit









Thanks for your attention