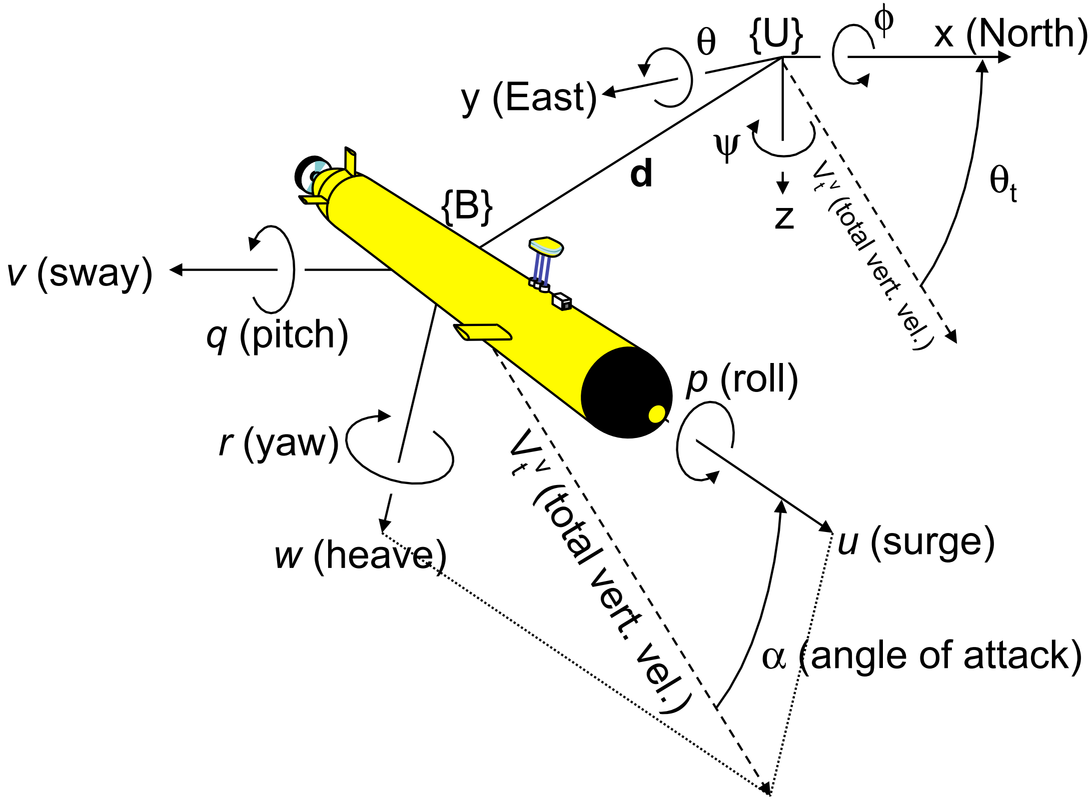
The use of dynamic model

Notation



Position w.r.t {U}

$$\eta = \begin{bmatrix} x & y & z & \varphi & \theta & \psi \end{bmatrix}^T$$

Velocity w.r.t {B}

$$\nu = \begin{bmatrix} u & v & w & p & q & r \end{bmatrix}^T$$

Kinematic relation

$$\dot{\eta} = R(\eta) \cdot \upsilon$$

Dynamic relation

$$\mathbf{F_B} = f_{Dyn}(\dot{\nu}, \nu, \eta, \mathbf{P})$$

$$\mathbf{P} = \begin{bmatrix} m_u & m_v & m_z & \ldots \end{bmatrix}^T$$

Actuation system

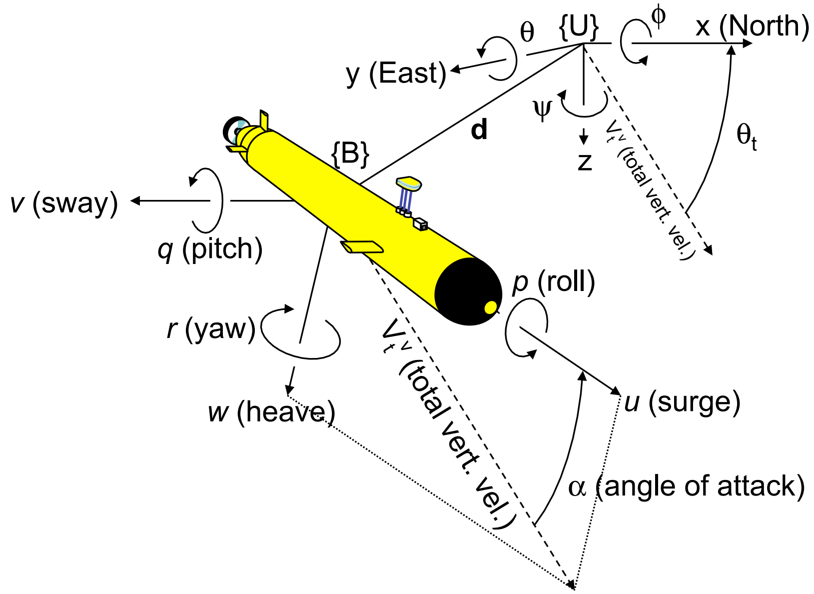
$$\mathbf{F_B} = \mathbf{A} \cdot \mathbf{F_m}$$

Actuators model

$$\mathbf{F_m} = \mathbf{M}(\chi)$$

Kinematic Model

$$\eta = \begin{bmatrix} x \\ y \\ z \\ \phi \\ \theta \\ \psi \end{bmatrix}$$



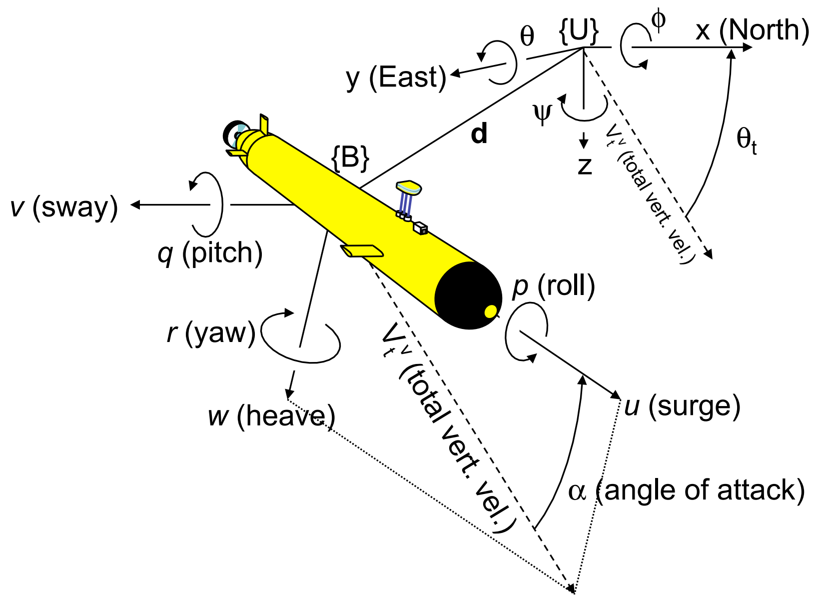
$$\upsilon = \begin{bmatrix} u \\ v \\ w \\ p \\ q \\ r \end{bmatrix}$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} \cos\psi\cdot\cos\theta & \cos\psi\cdot\sin\theta\cdot\sin\phi - \sin\psi\cdot\cos\phi & \cos\psi\cdot\sin\theta\cdot\cos\phi + \sin\psi\cdot\sin\phi & 0 & 0 & 0 \\ \sin\psi\cdot\cos\theta & \sin\psi\cdot\sin\theta\cdot\sin\phi + \cos\psi\cdot\cos\phi & \sin\psi\cdot\sin\theta\cdot\cos\phi - \cos\psi\cdot\sin\phi & 0 & 0 & 0 \\ -\sin\theta & \cos\theta\cdot\sin\phi & \cos\theta\cdot\cos\phi & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & \sin\phi\cdot\tan\theta & \cos\phi\cdot\tan\theta \\ 0 & 0 & 0 & 0 & \cos\phi & -\sin\phi \\ 0 & 0 & 0 & 0 & \dfrac{\sin\phi}{\cos\theta} & \dfrac{\cos\phi}{\cos\theta} \end{bmatrix} \cdot \begin{bmatrix} u \\ v \\ w \\ p \\ q \\ r \end{bmatrix}$$

$$\dot{\eta} = R \cdot \upsilon$$

Kinematic Model

$$\underbrace{\begin{bmatrix} x \\ y \\ z \\ \phi \\ \theta \\ \psi \end{bmatrix}}_{\eta}$$



$$\underbrace{\begin{bmatrix} u \\ v \\ w \\ p \\ q \\ r \end{bmatrix}}_{\upsilon}$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} \cos\psi\cdot\cos\theta & \cos\psi\cdot\sin\theta\cdot\sin\phi - \sin\psi\cdot\cos\phi & \cos\psi\cdot\sin\theta\cdot\cos\phi + \sin\psi\cdot\sin\phi & 0 & 0 & 0 \\ \sin\psi\cdot\cos\theta & \sin\psi\cdot\sin\theta\cdot\sin\phi + \cos\psi\cdot\cos\phi & \sin\psi\cdot\sin\theta\cdot\cos\phi - \cos\psi\cdot\sin\phi & 0 & 0 & 0 \\ -\sin\theta & \cos\theta\cdot\sin\phi & \cos\theta\cdot\cos\phi & 0 & 0 & 0 \\ 0 & 0 & & & \sin\phi\cdot\tan\theta & \cos\phi\cdot\tan\theta \\ 0 & 0 & & & \cos\phi & -\sin\phi \\ 0 & 0 & & & \frac{\sin\phi}{\cos\theta} & \frac{\cos\phi}{\cos\theta} \end{bmatrix} \cdot \begin{bmatrix} u \\ v \\ w \\ p \\ q \\ r \end{bmatrix}$$

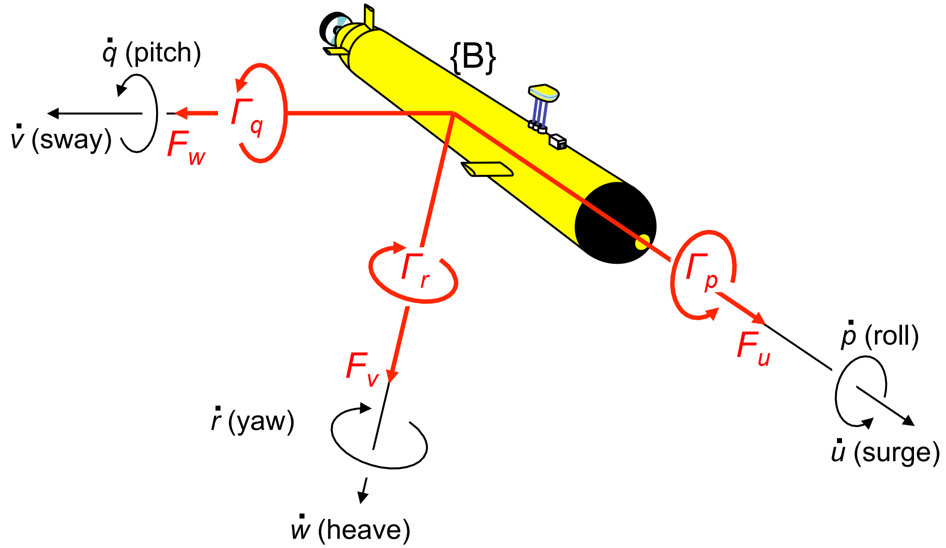
$$\theta = \pm\frac{\pi}{2}, \phi = \pm\frac{\pi}{2}$$

Singularities !

$$\dot{\eta} = R \cdot \upsilon$$

Dynamic Model

$$\underbrace{\begin{bmatrix} F_u \\ F_v \\ F_w \\ \Gamma_p \\ \Gamma_q \\ \Gamma_r \end{bmatrix}}_{\mathbf{F_B}}$$



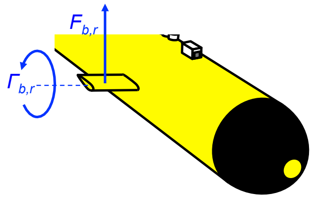
$$\underbrace{\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \\ \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix}}_{\dot{\nu}}$$

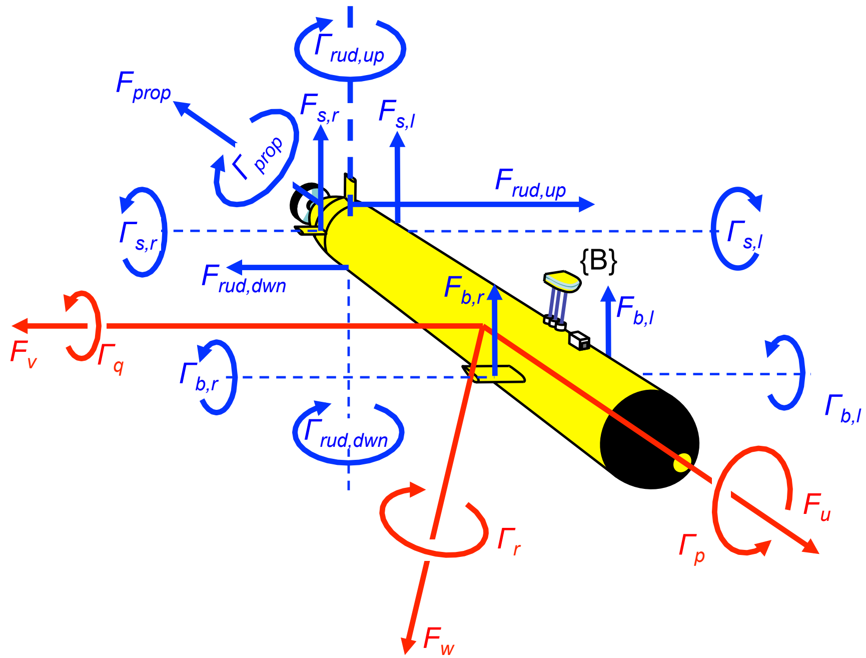
$$\begin{aligned}
F_u &= X_{\dot{u}} \cdot \dot{u} + X_{u \cdot |u|} \cdot u \cdot |u| + X_{w \cdot q} \cdot w \cdot q + X_{v \cdot r} \cdot v \cdot r + X_G(\eta) \\
F_v &= Y_{\dot{v}} \cdot \dot{v} + Y_{v \cdot |v|} \cdot v \cdot |v| + Y_{u \cdot r} \cdot u \cdot r + Y_{w \cdot p} \cdot w \cdot p + Y_G(\eta) \\
F_w &= Z_{\dot{w}} \cdot \dot{w} + Z_{w \cdot |w|} \cdot w \cdot |w| + Z_{u \cdot q} \cdot u \cdot q + Z_{v \cdot p} \cdot v \cdot p + Z_G(\eta) \\
\Gamma_p &= K_{\dot{p}} \cdot \dot{p} + K_{p \cdot |p|} \cdot p \cdot |p| + K_{q \cdot r} \cdot q \cdot r + K_v \cdot v + K_w \cdot w + K_G(\eta) \\
\Gamma_q &= M_{\dot{q}} \cdot \dot{q} + M_{q \cdot |q|} \cdot q \cdot |q| + M_{p \cdot r} \cdot p \cdot r + M_u \cdot u + M_w \cdot w + M_G(\eta) \\
\Gamma_r &= N_{\dot{r}} \cdot \dot{r} + N_{r \cdot |r|} \cdot r \cdot |r| + N_{p \cdot q} \cdot p \cdot q + N_u \cdot u + N_v \cdot v + N_G(\eta)
\end{aligned}$$

$$\mathbf{F_B} = f_{Dyn}(\dot{\nu}, \nu, \eta, \mathbf{P})$$

Actuation System Model

$$\underbrace{\begin{bmatrix} F_u \\ F_v \\ F_w \\ \Gamma_p \\ \Gamma_q \\ \Gamma_r \end{bmatrix}}_{\mathbf{F_B}}$$





$$\underbrace{\begin{bmatrix} F_{b,l} \\ \Gamma_{b,l} \\ F_{b,r} \\ \Gamma_{b,r} \\ F_{s,l} \\ \Gamma_{s,l} \\ F_{s,r} \\ \Gamma_{s,r} \\ F_{rud,up} \\ \Gamma_{rud,up} \\ F_{rud,dwn} \\ \Gamma_{rud,dwn} \\ F_{prop} \\ \Gamma_{prop} \end{bmatrix}}_{\mathbf{F_m}}$$

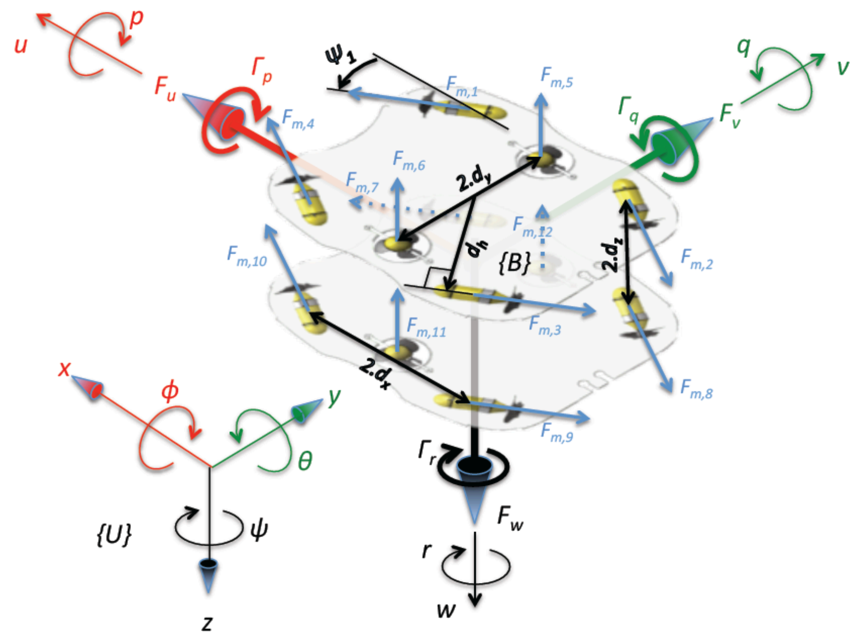
$$\mathbf{F_B} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 \\ 1 & 0 & -1 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ R & 0 & -R & 0 & R & 0 & -R & 0 & R & 0 & R & 0 & 0 & 1 \\ d_s & 1 & -d_s & -1 & d_b & 1 & -d_b & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -d_b & 1 & d_b & -1 & 0 & 0 \end{bmatrix} \cdot \mathbf{F_m}$$

(please check !)

$$\mathbf{F_B} = \mathbf{A} \cdot \mathbf{F_m}$$

Actuation System Model

$$\underbrace{\begin{bmatrix} F_u \\ F_v \\ F_w \\ \Gamma_p \\ \Gamma_q \\ \Gamma_r \end{bmatrix}}_{\mathbf{F_B}}$$



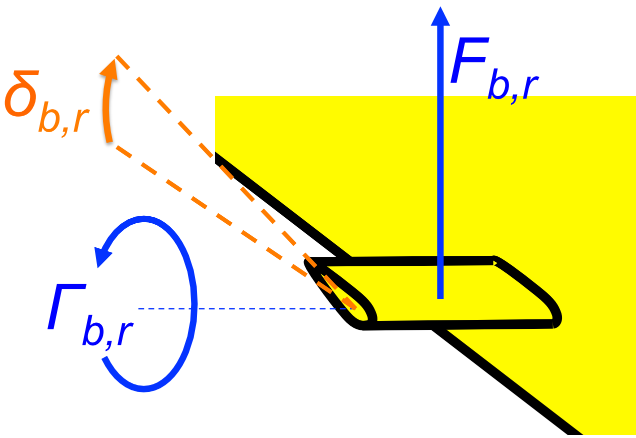
$$\underbrace{\begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \\ F_7 \\ F_8 \end{bmatrix}}_{\mathbf{F_m}}$$

$$\mathbf{A}_{5\times 8} = \begin{bmatrix} -.866 & -.866 & .866 & .866 & -.866 & -.866 & .866 & .866 \\ -.5 & .5 & .5 & -.5 & -.5 & .5 & .5 & -.5 \\ .1 & -.1 & -.1 & .1 & -.1 & .1 & .1 & -.1 \\ .173 & .173 & -.173 & -.173 & -.173 & -.173 & .173 & .173 \\ .226 & -.226 & .226 & -.226 & .226 & -.226 & .226 & -.226 \end{bmatrix}$$

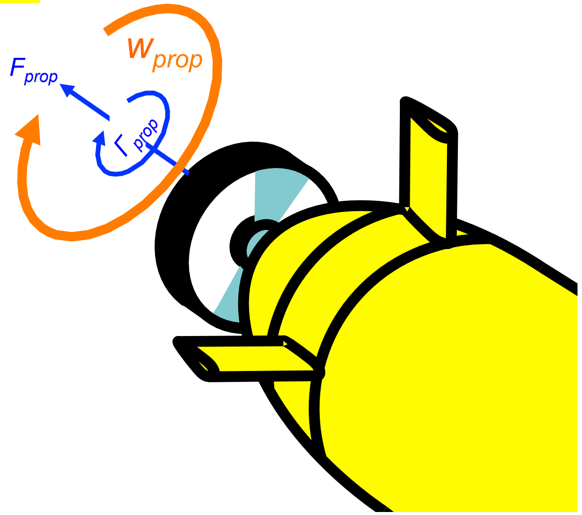
$$\mathbf{F_B} = \mathbf{A} \cdot \mathbf{F_m}$$

Actuators Model

$$\underbrace{\begin{bmatrix} F_{b,l} \\ \Gamma_{b,l} \\ F_{b,r} \\ \Gamma_{b,r} \\ F_{s,l} \\ \Gamma_{s,l} \\ F_{s,r} \\ \Gamma_{s,r} \\ F_{rud,up} \\ \Gamma_{rud,up} \\ F_{rud,dwn} \\ \Gamma_{rud,dwn} \\ F_{prop} \\ \Gamma_{prop} \end{bmatrix}}_{\mathbf{F_m}}$$

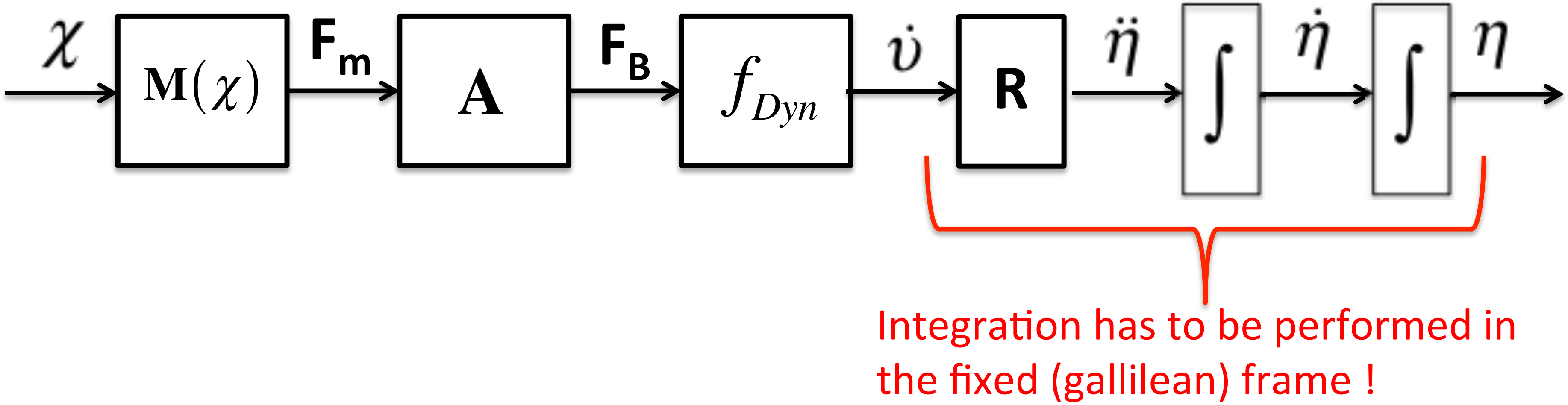


$$\mathbf{F}_m = \mathbf{M}(\chi)$$

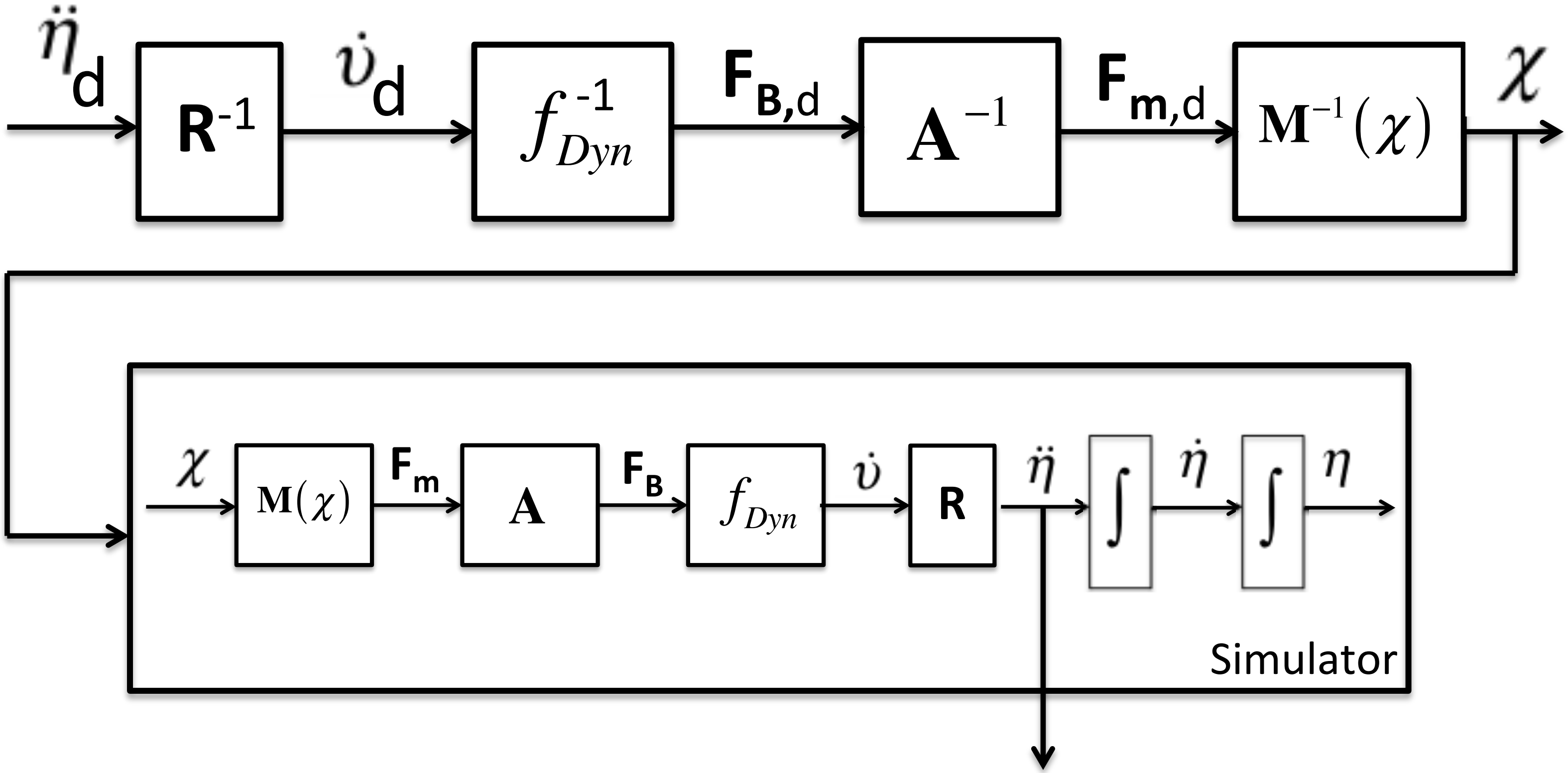


$$\underbrace{\begin{bmatrix} \delta_{b,l} \\ \delta_{b,r} \\ \delta_{s,l} \\ \delta_{s,r} \\ \delta_{rud,up} \\ \delta_{rud,dwn} \\ w_{prop} \end{bmatrix}}_{\chi}$$

Dynamic Simulation



Control as an inverse problem



The 'computed torque' solution : $\ddot{\eta} = \ddot{\eta}_d$

Everything works fine in simulation…

Closed loop indentification

- Station keeping test (null velocity stabilisation)
  - Station keeping around η_d
  - Once static regime is achieved, for $\chi^{\infty} : \nu = \mathbf{0}$

$$
\begin{aligned}
F_u &= X_{\dot{u}} \cdot \dot{u} + X_{u \cdot |u|} \cdot u \cdot |u| + X_{w \cdot q} \cdot w \cdot q + X_{v \cdot r} \cdot v \cdot r + X_G(\eta) \\
F_v &= Y_{\dot{v}} \cdot \dot{v} + Y_{v \cdot |v|} \cdot v \cdot |v| + Y_{u \cdot r} \cdot u \cdot r + Y_{w \cdot p} \cdot w \cdot p + Y_G(\eta) \\
F_w &= Z_{\dot{w}} \cdot \dot{w} + Z_{w \cdot |w|} \cdot w \cdot |w| + Z_{u \cdot q} \cdot u \cdot q + Z_{v \cdot p} \cdot v \cdot p + Z_G(\eta) \\
\Gamma_p &= K_{\dot{p}} \cdot \dot{p} + K_{p \cdot |p|} \cdot p \cdot |p| + K_{q \cdot r} \cdot q \cdot r + K_v \cdot v + K_w \cdot w + K_G(\eta) \\
\Gamma_q &= M_{\dot{q}} \cdot \dot{q} + M_{q \cdot |q|} \cdot q \cdot |q| + M_{p \cdot r} \cdot p \cdot r + M_u \cdot u + M_w \cdot w + M_G(\eta) \\
\Gamma_r &= N_{\dot{r}} \cdot \dot{r} + N_{r \cdot |r|} \cdot r \cdot |r| + N_{p \cdot q} \cdot p \cdot q + N_u \cdot u + N_v \cdot v + N_G(\eta)
\end{aligned}
$$

$$
\mathbf{F}_B^{\infty} = \mathbf{M}(\chi^{\infty}) = [\ X_G(\eta_d) \quad Y_G(\eta_d) \quad Z_G(\eta_d) \quad K_G(\eta_d) \quad M_G(\eta_d) \quad N_G(\eta_d)\ ]^T
$$

Closed loop indentification

- Independant velocity tests (along each DOF)
  - Control *u* to u_d. Once static regime is achieved,
  - for χ^{∞} : $\nu = [\ u_d \quad 0 \quad 0 \quad 0 \quad 0 \quad 0\ ]^T$

$$
\begin{aligned}
F_u &= X_{\dot{u}} \cdot \dot{u} + X_{u\cdot|u|} \cdot u \cdot |u| + X_{w\cdot q} \cdot w \cdot q + X_{v\cdot r} \cdot v \cdot r + X_G(\eta) \\
F_v &= Y_{\dot{v}} \cdot \dot{v} + Y_{v\cdot|v|} \cdot v \cdot |v| + Y_{u\cdot r} \cdot u \cdot r + Y_{w\cdot p} \cdot w \cdot p + Y_G(\eta) \\
F_w &= Z_{\dot{w}} \cdot \dot{w} + Z_{w\cdot|w|} \cdot w \cdot |w| + Z_{u\cdot q} \cdot u \cdot q + Z_{v\cdot p} \cdot v \cdot p + Z_G(\eta) \\
\Gamma_p &= K_{\dot{p}} \cdot \dot{p} + K_{p\cdot|p|} \cdot p \cdot |p| + K_{q\cdot r} \cdot q \cdot r + K_v \cdot v + K_w \cdot w + K_G(\eta) \\
\Gamma_q &= M_{\dot{q}} \cdot \dot{q} + M_{q\cdot|q|} \cdot q \cdot |q| + M_{p\cdot r} \cdot p \cdot r + M_u \cdot u + M_w \cdot w + M_G(\eta) \\
\Gamma_r &= N_{\dot{r}} \cdot \dot{r} + N_{r\cdot|r|} \cdot r \cdot |r| + N_{p\cdot q} \cdot p \cdot q + N_u \cdot u + N_v \cdot v + N_G(\eta)
\end{aligned}
$$

$$\mathbf{F}_B^{\infty} = \mathbf{M}(\chi^{\infty}) = \ldots$$

Closed loop indentification

- Independant velocity tests (along each DOF)
  - Control *v* to v_d. Once static regime is achieved,
  - for χ^{∞} : $v = [\ 0 \quad v_d \quad 0 \quad 0 \quad 0 \quad 0\ ]^T$

$$
\begin{aligned}
F_u &= \cancel{X_{\dot u} \cdot \dot u} + X_{u\cdot|u|} \cdot u \cdot |u| + \cancel{X_{w\cdot q} \cdot w \cdot q} + \cancel{X_{v\cdot r} \cdot v \cdot r} + X_G(\eta) \\
F_v &= \cancel{Y_{\dot v} \cdot \dot v} + Y_{v\cdot|v|} \cdot v \cdot |v| + \cancel{Y_{u\cdot r} \cdot u \cdot r} + \cancel{Y_{w\cdot p} \cdot w \cdot p} + Y_G(\eta) \\
F_w &= \cancel{Z_{\dot w} \cdot \dot w} + \cancel{Z_{w\cdot|w|} \cdot w \cdot |w|} + \cancel{Z_{u\cdot q} \cdot u \cdot q} + \cancel{Z_{v\cdot p} \cdot v \cdot p} + Z_G(\eta) \\
\Gamma_p &= \cancel{K_{\dot p} \cdot \dot p} + \cancel{K_{p\cdot|p|} \cdot p \cdot |p|} + \cancel{K_{q\cdot r} \cdot q \cdot r} + K_v \cdot v + \cancel{K_w \cdot w} + K_G(\eta) \\
\Gamma_q &= \cancel{M_{\dot q} \cdot \dot q} + \cancel{M_{q\cdot|q|} \cdot q \cdot |q|} + \cancel{M_{p\cdot r} \cdot p \cdot r} + M_u \cdot u + \cancel{M_w \cdot w} + M_G(\eta) \\
\Gamma_r &= \cancel{N_{\dot r} \cdot \dot r} + \cancel{N_{r\cdot|r|} \cdot r \cdot |r|} + \cancel{N_{p\cdot q} \cdot p \cdot q} + N_u \cdot u + N_v \cdot v + N_G(\eta)
\end{aligned}
$$

$$\mathbf{F}_B^{\infty} = \mathbf{M}(\chi^{\infty}) = \ldots$$

Closed loop indentification

- Independant velocity tests (along each DOF)
  - Control w to w_d. Once static regime is achieved,
  - for χ^{∞} : $\nu = [\ 0 \quad 0 \quad w_d \quad 0 \quad 0 \quad 0\ ]^T$

$$
\begin{aligned}
F_u &= \cancel{X_{\dot{u}} \cdot \dot{u}} + X_{u\cdot|u|} \cdot u \cdot |u| + \cancel{X_{w\cdot q} \cdot w \cdot q} + \cancel{X_{v\cdot r} \cdot v \cdot r} + X_G(\eta) \\
F_v &= \cancel{Y_{\dot{v}} \cdot \dot{v}} + Y_{v\cdot|v|} \cdot v \cdot |v| + \cancel{Y_{u\cdot r} \cdot u \cdot r} + \cancel{Y_{w\cdot p} \cdot w \cdot p} + Y_G(\eta) \\
F_w &= \cancel{Z_{\dot{w}} \cdot \dot{w}} + Z_{w\cdot|w|} \cdot w \cdot |w| + \cancel{Z_{u\cdot q} \cdot u \cdot q} + \cancel{Z_{v\cdot p} \cdot v \cdot p} + Z_G(\eta) \\
\Gamma_p &= \cancel{K_{\dot{p}} \cdot \dot{p}} + \cancel{K_{p\cdot|p|} \cdot p \cdot |p|} + \cancel{K_{q\cdot r} \cdot q \cdot r} + K_v \cdot v + K_w \cdot w + K_G(\eta) \\
\Gamma_q &= \cancel{M_{\dot{q}} \cdot \dot{q}} + \cancel{M_{q\cdot|q|} \cdot q \cdot |q|} + \cancel{M_{p\cdot r} \cdot p \cdot r} + M_u \cdot u + M_w \cdot w + M_G(\eta) \\
\Gamma_r &= \cancel{N_{\dot{r}} \cdot \dot{r}} + \cancel{N_{r\cdot|r|} \cdot r \cdot |r|} + \cancel{N_{p\cdot q} \cdot p \cdot q} + N_u \cdot u + N_v \cdot v + N_G(\eta)
\end{aligned}
$$

$$\mathbf{F}_B^{\infty} = \mathbf{M}(\chi^{\infty}) = \ldots$$

Closed loop indentification

- Independant velocity tests (along each DOF)
  - Control p to p_d. Once static regime is achieved,
  - for χ^{∞} : $\nu = [\ 0 \quad 0 \quad 0 \quad p_d \quad 0 \quad 0\ ]^T$

$$
\begin{aligned}
F_u &= X_{\dot{u}} \cdot \dot{u} + X_{u\cdot|u|} \cdot u \cdot |u| + X_{w\cdot q} \cdot w \cdot q + X_{v\cdot r} \cdot v \cdot r + X_G(\eta) \\
F_v &= Y_{\dot{v}} \cdot \dot{v} + Y_{v\cdot|v|} \cdot v \cdot |v| + Y_{u\cdot r} \cdot u \cdot r + Y_{w\cdot p} \cdot w \cdot p + Y_G(\eta) \\
F_w &= Z_{\dot{w}} \cdot \dot{w} + Z_{w\cdot|w|} \cdot w \cdot |w| + Z_{u\cdot q} \cdot u \cdot q + Z_{v\cdot p} \cdot v \cdot p + Z_G(\eta) \\
\Gamma_p &= K_{\dot{p}} \cdot \dot{p} + K_{p\cdot|p|} \cdot p \cdot |p| + K_{q\cdot r} \cdot q \cdot r + K_v \cdot v + K_w \cdot w + K_G(\eta) \\
\Gamma_q &= M_{\dot{q}} \cdot \dot{q} + M_{q\cdot|q|} \cdot q \cdot |q| + M_{p\cdot r} \cdot p \cdot r + M_u \cdot u + M_w \cdot w + M_G(\eta) \\
\Gamma_r &= N_{\dot{r}} \cdot \dot{r} + N_{r\cdot|r|} \cdot r \cdot |r| + N_{p\cdot q} \cdot p \cdot q + N_u \cdot u + N_v \cdot v + N_G(\eta)
\end{aligned}
$$

$$\mathbf{F}_B^{\infty} = \mathbf{M}(\chi^{\infty}) = \ldots$$

Closed loop indentification

- Independant velocity tests (along each DOF)
  - Control q to q_d. Once static regime is achieved,
  - for χ^{∞} : $\nu = [\ 0 \quad 0 \quad 0 \quad 0 \quad q_d \quad 0\ ]^T$

$$
\begin{aligned}
F_u &= \cancel{X_{\dot{u}} \cdot \dot{u}} + X_{u \cdot |u|} \cdot u \cdot |u| + \cancel{X_{w \cdot q} \cdot w \cdot q} + \cancel{X_{v \cdot r} \cdot v \cdot r} + X_G(\eta) \\
F_v &= \cancel{Y_{\dot{v}} \cdot \dot{v}} + Y_{v \cdot |v|} \cdot v \cdot |v| + \cancel{Y_{u \cdot r} \cdot u \cdot r} + \cancel{Y_{w \cdot p} \cdot w \cdot p} + Y_G(\eta) \\
F_w &= \cancel{Z_{\dot{w}} \cdot \dot{w}} + Z_{w \cdot |w|} \cdot w \cdot |w| + \cancel{Z_{u \cdot q} \cdot u \cdot q} + \cancel{Z_{v \cdot p} \cdot v \cdot p} + Z_G(\eta) \\
\Gamma_p &= \cancel{K_{\dot{p}} \cdot \dot{p}} + K_{p \cdot |p|} \cdot p \cdot |p| + \cancel{K_{q \cdot r} \cdot q \cdot r} + K_v \cdot v + K_w \cdot w + K_G(\eta) \\
\Gamma_q &= \cancel{M_{\dot{q}} \cdot \dot{q}} + M_{q \cdot |q|} \cdot q \cdot |q| + \cancel{M_{p \cdot r} \cdot p \cdot r} + M_u \cdot u + M_w \cdot w + M_G(\eta) \\
\Gamma_r &= \cancel{N_{\dot{r}} \cdot \dot{r}} + \cancel{N_{r \cdot |r|} \cdot r \cdot |r|} + \cancel{N_{p \cdot q} \cdot p \cdot q} + N_u \cdot u + N_v \cdot v + N_G(\eta)
\end{aligned}
$$

$$\mathbf{F}_B^{\infty} = \mathbf{M}(\chi^{\infty}) = \ldots$$

Closed loop indentification

- Independant velocity tests (along each DOF)
  - Control r to r_d. Once static regime is achieved,
  - for χ^{∞} : $\nu = [\ 0\quad 0\quad 0\quad 0\quad 0\quad r_d\ ]^T$

$$
\begin{aligned}
F_u &= \cancel{X_{\dot u}\cdot \dot u} + X_{u\cdot|u|}\cdot u\cdot|u| + \cancel{X_{w\cdot q}\cdot w\cdot q} + \cancel{X_{v\cdot r}\cdot v\cdot r} + X_G(\eta)\\
F_v &= \cancel{Y_{\dot v}\cdot \dot v} + Y_{v\cdot|v|}\cdot v\cdot|v| + \cancel{Y_{u\cdot r}\cdot u\cdot r} + \cancel{Y_{w\cdot p}\cdot w\cdot p} + Y_G(\eta)\\
F_w &= \cancel{Z_{\dot w}\cdot \dot w} + Z_{w\cdot|w|}\cdot w\cdot|w| + \cancel{Z_{u\cdot q}\cdot u\cdot q} + \cancel{Z_{v\cdot p}\cdot v\cdot p} + Z_G(\eta)\\
\Gamma_p &= \cancel{K_{\dot p}\cdot \dot p} + K_{p\cdot|p|}\cdot p\cdot|p| + \cancel{K_{q\cdot r}\cdot q\cdot r} + K_v\cdot v + K_w\cdot w + K_G(\eta)\\
\Gamma_q &= \cancel{M_{\dot q}\cdot \dot q} + M_{q\cdot|q|}\cdot q\cdot|q| + \cancel{M_{p\cdot r}\cdot p\cdot r} + M_u\cdot u + M_w\cdot w + M_G(\eta)\\
\Gamma_r &= \cancel{N_{\dot r}\cdot \dot r} + N_{r\cdot|r|}\cdot r\cdot|r| + \cancel{N_{p\cdot q}\cdot p\cdot q} + N_u\cdot u + N_v\cdot v + N_G(\eta)
\end{aligned}
$$

$$\mathbf{F}_B^{\infty} = \mathbf{M}(\chi^{\infty}) = \ldots$$

Closed loop indentification

- cross velocity tests (along each DOF)
  - Control *u* to u_d *and r to* r_d. Once static reg. is achieved,
  - for χ^∞ : $\nu = [\ u_d \quad 0 \quad 0 \quad 0 \quad 0 \quad r_d\ ]^T$

$$
\begin{aligned}
F_u &= \cancel{X_{\dot u} \cdot \dot u} + X_{u\cdot|u|} \cdot u \cdot |u| + \cancel{X_{w\cdot q} \cdot w \cdot q} + \cancel{X_{v\cdot r} \cdot v \cdot r} + X_G(\eta) \\
F_v &= \cancel{Y_{\dot v} \cdot \dot v} + Y_{v\cdot|v|} \cdot v \cdot |v| + Y_{u\cdot r} \cdot u \cdot r + \cancel{Y_{w\cdot p} \cdot w \cdot p} + Y_G(\eta) \\
F_w &= \cancel{Z_{\dot w} \cdot \dot w} + Z_{w\cdot|w|} \cdot w \cdot |w| + \cancel{Z_{u\cdot q} \cdot u \cdot q} + \cancel{Z_{v\cdot p} \cdot v \cdot p} + Z_G(\eta) \\
\Gamma_p &= \cancel{K_{\dot p} \cdot \dot p} + K_{p\cdot|p|} \cdot p \cdot |p| + \cancel{K_{q\cdot r} \cdot q \cdot r} + K_v \cdot v + K_w \cdot w + K_G(\eta) \\
\Gamma_q &= \cancel{M_{\dot q} \cdot \dot q} + M_{q\cdot|q|} \cdot q \cdot |q| + \cancel{M_{p\cdot r} \cdot p \cdot r} + M_u \cdot u + M_w \cdot w + M_G(\eta) \\
\Gamma_r &= \cancel{N_{\dot r} \cdot \dot r} + N_{r\cdot|r|} \cdot r \cdot |r| + \cancel{N_{p\cdot q} \cdot p \cdot q} + N_u \cdot u + N_v \cdot v + N_G(\eta)
\end{aligned}
$$

$$\mathbf{F}_B^\infty = \mathbf{M}(\chi^\infty) = \ldots$$

Closed loop indentification

- cross velocity tests (along each DOF)
  - Control *v* to v_d *and r to* r_d. Once static reg. is achieved,
  - for χ^∞ : $\nu = [\ 0 \quad v_d \quad 0 \quad 0 \quad 0 \quad r_d\ ]^T$

$$
\begin{aligned}
F_u &= X_{\dot{u}} \cdot \dot{u} + X_{u\cdot|u|} \cdot u \cdot |u| + X_{w\cdot q} \cdot w \cdot q + X_{v\cdot r} \cdot v \cdot r + X_G(\eta) \\
F_v &= Y_{\dot{v}} \cdot \dot{v} + Y_{v\cdot|v|} \cdot v \cdot |v| + Y_{u\cdot r} \cdot u \cdot r + Y_{w\cdot p} \cdot w \cdot p + Y_G(\eta) \\
F_w &= Z_{\dot{w}} \cdot \dot{w} + Z_{w\cdot|w|} \cdot w \cdot |w| + Z_{u\cdot q} \cdot u \cdot q + Z_{v\cdot p} \cdot v \cdot p + Z_G(\eta) \\
\Gamma_p &= K_{\dot{p}} \cdot \dot{p} + K_{p\cdot|p|} \cdot p \cdot |p| + K_{q\cdot r} \cdot q \cdot r + K_v \cdot v + K_w \cdot w + K_G(\eta) \\
\Gamma_q &= M_{\dot{q}} \cdot \dot{q} + M_{q\cdot|q|} \cdot q \cdot |q| + M_{p\cdot r} \cdot p \cdot r + M_u \cdot u + M_w \cdot w + M_G(\eta) \\
\Gamma_r &= N_{\dot{r}} \cdot \dot{r} + N_{r\cdot|r|} \cdot r \cdot |r| + N_{p\cdot q} \cdot p \cdot q + N_u \cdot u + N_v \cdot v + N_G(\eta)
\end{aligned}
$$

$$\mathbf{F}_B^\infty = \mathbf{M}(\chi^\infty) = \dots$$

Closed loop indentification

- cross velocity tests (along each DOF)
  - Control *w* to w_d *and q to* q_d. Once static reg. is ach.,
  - for χ^∞ : $\nu = [\; 0 \quad 0 \quad w_d \quad 0 \quad q_d \quad 0 \;]^T$

$$
\begin{aligned}
F_u &= \cancel{X_{\dot{u}} \cdot \dot{u}} + X_{u\cdot|u|} \cdot u \cdot |u| + X_{w\cdot q} \cdot w \cdot q + X_{v\cdot r} \cdot v \cdot r + X_G(\eta) \\
F_v &= \cancel{Y_{\dot{v}} \cdot \dot{v}} + Y_{v\cdot|v|} \cdot v \cdot |v| + Y_{u\cdot r} \cdot u \cdot r + \cancel{Y_{w\cdot p} \cdot w \cdot p} + Y_G(\eta) \\
F_w &= \cancel{Z_{\dot{w}} \cdot \dot{w}} + Z_{w\cdot|w|} \cdot w \cdot |w| + \cancel{Z_{u\cdot q} \cdot u \cdot q} + \cancel{Z_{v\cdot p} \cdot v \cdot p} + Z_G(\eta) \\
\Gamma_p &= \cancel{K_{\dot{p}} \cdot \dot{p}} + K_{p\cdot|p|} \cdot p \cdot |p| + \cancel{K_{q\cdot r} \cdot q \cdot r} + K_v \cdot v + K_w \cdot w + K_G(\eta) \\
\Gamma_q &= \cancel{M_{\dot{q}} \cdot \dot{q}} + M_{q\cdot|q|} \cdot q \cdot |q| + \cancel{M_{p\cdot r} \cdot p \cdot r} + M_u \cdot u + M_w \cdot w + M_G(\eta) \\
\Gamma_r &= \cancel{N_{\dot{r}} \cdot \dot{r}} + N_{r\cdot|r|} \cdot r \cdot |r| + \cancel{N_{p\cdot q} \cdot p \cdot q} + N_u \cdot u + N_v \cdot v + N_G(\eta)
\end{aligned}
$$

$$\mathbf{F}_B^\infty = \mathbf{M}(\chi^\infty) = \ldots$$

Closed loop indentification

- cross velocity tests (along each DOF)
  - Control *w* to w_d *and p to* p_d. Once static reg. is ach.,
  - for χ^{∞} : $\nu = [\ 0 \quad 0 \quad w_d \quad p_d \quad 0 \quad 0\ ]^T$

$$
\begin{aligned}
F_u &= \cancel{X_{\dot{u}} \cdot \dot{u}} + X_{u \cdot |u|} \cdot u \cdot |u| + X_{w \cdot q} \cdot w \cdot q + X_{v \cdot r} \cdot v \cdot r + X_G(\eta) \\
F_v &= \cancel{Y_{\dot{v}} \cdot \dot{v}} + Y_{v \cdot |v|} \cdot v \cdot |v| + Y_{u \cdot r} \cdot u \cdot r + Y_{w \cdot p} \cdot w \cdot p + Y_G(\eta) \\
F_w &= \cancel{Z_{\dot{w}} \cdot \dot{w}} + Z_{w \cdot |w|} \cdot w \cdot |w| + \cancel{Z_{u \cdot q} \cdot u \cdot q} + \cancel{Z_{v \cdot p} \cdot v \cdot p} + Z_G(\eta) \\
\Gamma_p &= \cancel{K_{\dot{p}} \cdot \dot{p}} + K_{p \cdot |p|} \cdot p \cdot |p| + \cancel{K_{q \cdot r} \cdot q \cdot r} + K_v \cdot v + K_w \cdot w + K_G(\eta) \\
\Gamma_q &= \cancel{M_{\dot{q}} \cdot \dot{q}} + M_{q \cdot |q|} \cdot q \cdot |q| + \cancel{M_{p \cdot r} \cdot p \cdot r} + M_u \cdot u + M_w \cdot w + M_G(\eta) \\
\Gamma_r &= \cancel{N_{\dot{r}} \cdot \dot{r}} + N_{r \cdot |r|} \cdot r \cdot |r| + \cancel{N_{p \cdot q} \cdot p \cdot q} + N_u \cdot u + N_v \cdot v + N_G(\eta)
\end{aligned}
$$

$$\mathbf{F}_B^{\infty} = \mathbf{M}(\chi^{\infty}) = \ldots$$

Closed loop indentification

- cross velocity tests (along each DOF)
  – Control v to v_d *and p to p_d*. Once static reg. is ach.,
  – for χ^{∞} : $v = [\ 0 \quad v_d \quad 0 \quad p_d \quad 0 \quad 0\ ]^T$

$$
\begin{aligned}
F_u &= X_{\dot{u}} \cdot \dot{u} + X_{u\cdot|u|} \cdot u \cdot |u| + X_{w\cdot q} \cdot w \cdot q + X_{v\cdot r} \cdot v \cdot r + X_G(\eta) \\
F_v &= Y_{\dot{v}} \cdot \dot{v} + Y_{v\cdot|v|} \cdot v \cdot |v| + Y_{u\cdot r} \cdot u \cdot r + Y_{w\cdot p} \cdot w \cdot p + Y_G(\eta) \\
F_w &= Z_{\dot{w}} \cdot \dot{w} + Z_{w\cdot|w|} \cdot w \cdot |w| + Z_{u\cdot q} \cdot u \cdot q + Z_{v\cdot p} \cdot v \cdot p + Z_G(\eta) \\
\Gamma_p &= K_{\dot{p}} \cdot \dot{p} + K_{p\cdot|p|} \cdot p \cdot |p| + K_{q\cdot r} \cdot q \cdot r + K_v \cdot v + K_w \cdot w + K_G(\eta) \\
\Gamma_q &= M_{\dot{q}} \cdot \dot{q} + M_{q\cdot|q|} \cdot q \cdot |q| + M_{p\cdot r} \cdot p \cdot r + M_u \cdot u + M_w \cdot w + M_G(\eta) \\
\Gamma_r &= N_{\dot{r}} \cdot \dot{r} + N_{r\cdot|r|} \cdot r \cdot |r| + N_{p\cdot q} \cdot p \cdot q + N_u \cdot u + N_v \cdot v + N_G(\eta)
\end{aligned}
$$

$$\mathbf{F}_B^{\infty} = \mathbf{M}(\chi^{\infty}) = \ldots$$

Closed loop indentification

- cross velocity tests (along each DOF)
  - Control *u* to u_d *and q to* q_d. Once static reg. is ach.,
  - for χ^{∞} : $v = [\; u_d \quad 0 \quad 0 \quad 0 \quad q_d \quad 0 \;]^T$

$$
\begin{aligned}
F_u &= \cancel{X_{\dot{u}} \cdot \dot{u}} + X_{u\cdot|u|} \cdot u \cdot |u| + X_{w\cdot q} \cdot w \cdot q + X_{v\cdot r} \cdot v \cdot r + X_G(\eta) \\
F_v &= \cancel{Y_{\dot{v}} \cdot \dot{v}} + Y_{v\cdot|v|} \cdot v \cdot |v| + Y_{u\cdot r} \cdot u \cdot r + Y_{w\cdot p} \cdot w \cdot p + Y_G(\eta) \\
F_w &= \cancel{Z_{\dot{w}} \cdot \dot{w}} + Z_{w\cdot|w|} \cdot w \cdot |w| + Z_{u\cdot q} \cdot u \cdot q + Z_{v\cdot p} \cdot v \cdot p + Z_G(\eta) \\
\Gamma_p &= \cancel{K_{\dot{p}} \cdot \dot{p}} + K_{p\cdot|p|} \cdot p \cdot |p| + \cancel{K_{q\cdot r} \cdot q \cdot r} + K_v \cdot v + K_w \cdot w + K_G(\eta) \\
\Gamma_q &= \cancel{M_{\dot{q}} \cdot \dot{q}} + M_{q\cdot|q|} \cdot q \cdot |q| + \cancel{M_{p\cdot r} \cdot p \cdot r} + M_u \cdot u + M_w \cdot w + M_G(\eta) \\
\Gamma_r &= \cancel{N_{\dot{r}} \cdot \dot{r}} + N_{r\cdot|r|} \cdot r \cdot |r| + \cancel{N_{p\cdot q} \cdot p \cdot q} + N_u \cdot u + N_v \cdot v + N_G(\eta)
\end{aligned}
$$

$$\mathbf{F}_B^{\infty} = \mathbf{M}(\chi^{\infty}) = \ldots$$

Closed loop indentification

- cross velocity tests (along each DOF)
  - Control *q* to q_d *and r to* r_d. Once static reg. is ach.,
  - for χ^{∞} : $\nu = [\ 0 \quad 0 \quad 0 \quad 0 \quad q_d \quad r_d\ ]^T$

$$
\begin{aligned}
F_u &= X_{\dot{u}} \cdot \dot{u} + X_{u\cdot|u|} \cdot u \cdot |u| + X_{w\cdot q} \cdot w \cdot q + X_{v\cdot r} \cdot v \cdot r + X_G(\eta) \\
F_v &= Y_{\dot{v}} \cdot \dot{v} + Y_{v\cdot|v|} \cdot v \cdot |v| + Y_{u\cdot r} \cdot u \cdot r + Y_{w\cdot p} \cdot w \cdot p + Y_G(\eta) \\
F_w &= Z_{\dot{w}} \cdot \dot{w} + Z_{w\cdot|w|} \cdot w \cdot |w| + Z_{u\cdot q} \cdot u \cdot q + Z_{v\cdot p} \cdot v \cdot p + Z_G(\eta) \\
\Gamma_p &= K_{\dot{p}} \cdot \dot{p} + K_{p\cdot|p|} \cdot p \cdot |p| + K_{q\cdot r} \cdot q \cdot r + K_v \cdot v + K_w \cdot w + K_G(\eta) \\
\Gamma_q &= M_{\dot{q}} \cdot \dot{q} + M_{q\cdot|q|} \cdot q \cdot |q| + M_{p\cdot r} \cdot p \cdot r + M_u \cdot u + M_w \cdot w + M_G(\eta) \\
\Gamma_r &= N_{\dot{r}} \cdot \dot{r} + N_{r\cdot|r|} \cdot r \cdot |r| + N_{p\cdot q} \cdot p \cdot q + N_u \cdot u + N_v \cdot v + N_G(\eta)
\end{aligned}
$$

$$\mathbf{F}_B^{\infty} = \mathbf{M}(\chi^{\infty}) = \ldots$$

Closed loop indentification

- cross velocity tests (along each DOF)
  - Control *p* to p_d *and r to* r_d. Once static reg. is ach.,
  - for χ^∞ : $\nu = [\ 0\ \ 0\ \ 0\ \ p_d\ \ 0\ \ r_d\ ]^T$

$$
\begin{aligned}
F_u &= X_{\dot u} \cdot \dot u + X_{u\cdot|u|} \cdot u \cdot |u| + X_{w\cdot q} \cdot w \cdot q + X_{v\cdot r} \cdot v \cdot r + X_G(\eta) \\
F_v &= Y_{\dot v} \cdot \dot v + Y_{v\cdot|v|} \cdot v \cdot |v| + Y_{u\cdot r} \cdot u \cdot r + Y_{w\cdot p} \cdot w \cdot p + Y_G(\eta) \\
F_w &= Z_{\dot w} \cdot \dot w + Z_{w\cdot|w|} \cdot w \cdot |w| + Z_{u\cdot q} \cdot u \cdot q + Z_{v\cdot p} \cdot v \cdot p + Z_G(\eta) \\
\Gamma_p &= K_{\dot p} \cdot \dot p + K_{p\cdot|p|} \cdot p \cdot |p| + K_{q\cdot r} \cdot q \cdot r + K_v \cdot v + K_w \cdot w + K_G(\eta) \\
\Gamma_q &= M_{\dot q} \cdot \dot q + M_{q\cdot|q|} \cdot q \cdot |q| + M_{p\cdot r} \cdot p \cdot r + M_u \cdot u + M_w \cdot w + M_G(\eta) \\
\Gamma_r &= N_{\dot r} \cdot \dot r + N_{r\cdot|r|} \cdot r \cdot |r| + N_{p\cdot q} \cdot p \cdot q + N_u \cdot u + N_v \cdot v + N_G(\eta)
\end{aligned}
$$

$$\mathbf{F}_B^\infty = \mathbf{M}(\chi^\infty) = \dots$$

Closed loop indentification

- cross velocity tests (along each DOF)
  - Control *p* to p_d *and q to* q_d. Once static reg. is ach.,
  - for χ^{∞} : $v = [\begin{matrix} 0 & 0 & 0 & p_d & q_q & 0 \end{matrix}]^T$

$$
\begin{aligned}
F_u &= \cancel{X_{\dot{u}} \cdot \dot{u}} + X_{u \cdot |u|} \cdot u \cdot |u| + X_{w \cdot q} \cdot w \cdot q + X_{v \cdot r} \cdot v \cdot r + X_G(\eta) \\
F_v &= \cancel{Y_{\dot{v}} \cdot \dot{v}} + Y_{v \cdot |v|} \cdot v \cdot |v| + Y_{u \cdot r} \cdot u \cdot r + Y_{w \cdot p} \cdot w \cdot p + Y_G(\eta) \\
F_w &= \cancel{Z_{\dot{w}} \cdot \dot{w}} + Z_{w \cdot |w|} \cdot w \cdot |w| + Z_{u \cdot q} \cdot u \cdot q + Z_{v \cdot p} \cdot v \cdot p + Z_G(\eta) \\
\Gamma_p &= \cancel{K_{\dot{p}} \cdot \dot{p}} + K_{p \cdot |p|} \cdot p \cdot |p| + K_{q \cdot r} \cdot q \cdot r + K_v \cdot v + K_w \cdot w + K_G(\eta) \\
\Gamma_q &= \cancel{M_{\dot{q}} \cdot \dot{q}} + M_{q \cdot |q|} \cdot q \cdot |q| + M_{p \cdot r} \cdot p \cdot r + M_u \cdot u + M_w \cdot w + M_G(\eta) \\
\Gamma_r &= \cancel{N_{\dot{r}} \cdot \dot{r}} + N_{r \cdot |r|} \cdot r \cdot |r| + N_{p \cdot q} \cdot p \cdot q + N_u \cdot u + N_v \cdot v + N_G(\eta)
\end{aligned}
$$

$$\mathbf{F}_B^{\infty} = \mathbf{M}(\chi^{\infty}) = \ldots$$

Closed loop indentification

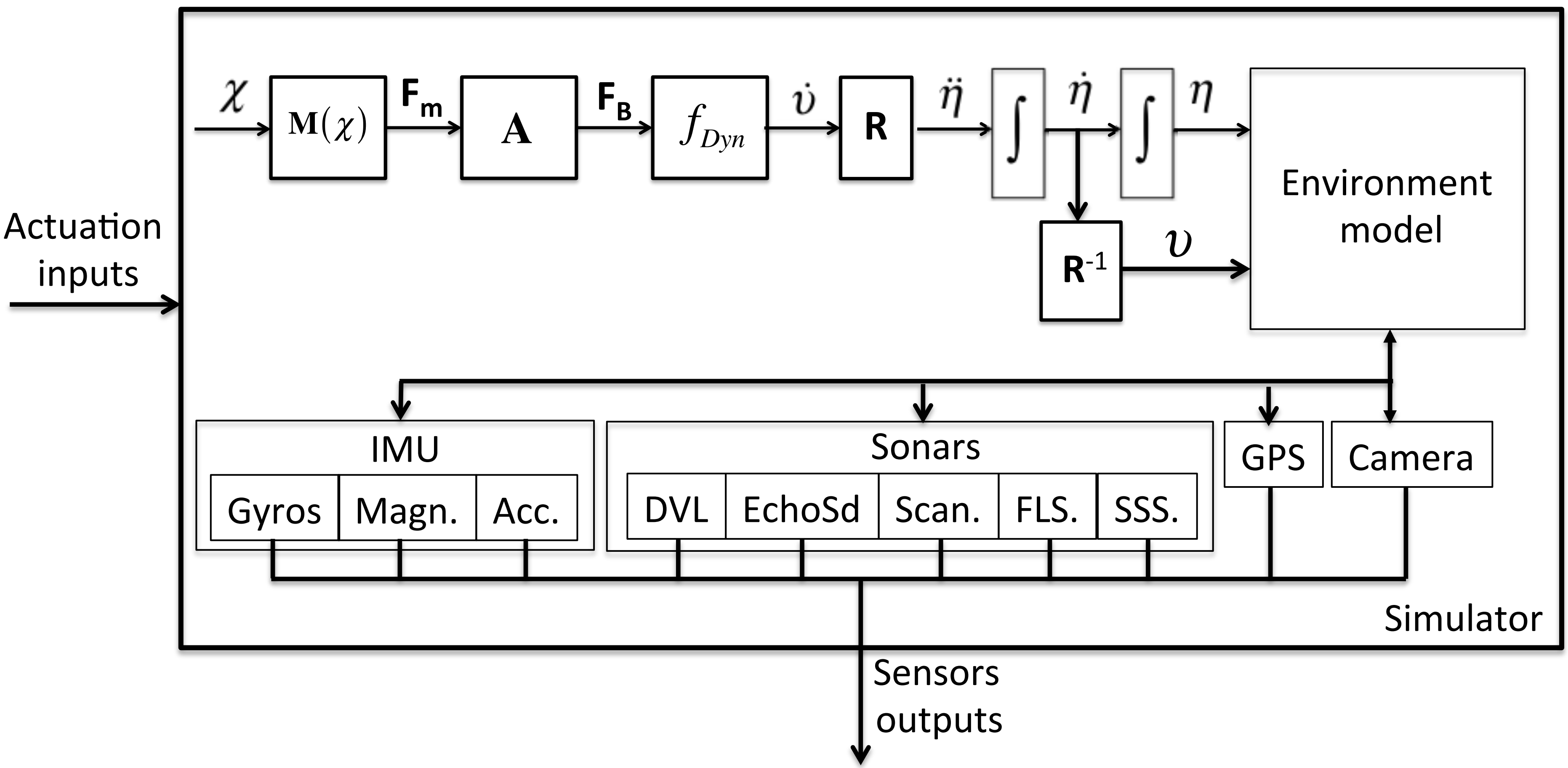
- Added mass (along each DOF)
  - Requires an acceleration control
  - Simpler to rely on theoretical models…

$$
\begin{aligned}
F_u &= X_{\dot{u}} \cdot \dot{u} + X_{u \cdot |u|} \cdot u \cdot |u| + X_{w \cdot q} \cdot w \cdot q + X_{v \cdot r} \cdot v \cdot r + X_G(\eta) \\
F_v &= Y_{\dot{v}} \cdot \dot{v} + Y_{v \cdot |v|} \cdot v \cdot |v| + Y_{u \cdot r} \cdot u \cdot r + Y_{w \cdot p} \cdot w \cdot p + Y_G(\eta) \\
F_w &= Z_{\dot{w}} \cdot \dot{w} + Z_{w \cdot |w|} \cdot w \cdot |w| + Z_{u \cdot q} \cdot u \cdot q + Z_{v \cdot p} \cdot v \cdot p + Z_G(\eta) \\
\Gamma_p &= K_{\dot{p}} \cdot \dot{p} + K_{p \cdot |p|} \cdot p \cdot |p| + K_{q \cdot r} \cdot q \cdot r + K_v \cdot v + K_w \cdot w + K_G(\eta) \\
\Gamma_q &= M_{\dot{q}} \cdot \dot{q} + M_{q \cdot |q|} \cdot q \cdot |q| + M_{p \cdot r} \cdot p \cdot r + M_u \cdot u + M_w \cdot w + M_G(\eta) \\
\Gamma_r &= \underbrace{N_{\dot{r}} \cdot \dot{r}}_{\text{Theoretical models}} + N_{r \cdot |r|} \cdot r \cdot |r| + N_{p \cdot q} \cdot p \cdot q + N_u \cdot u + N_v \cdot v + N_G(\eta)
\end{aligned}
$$

-> 16 experimentations !

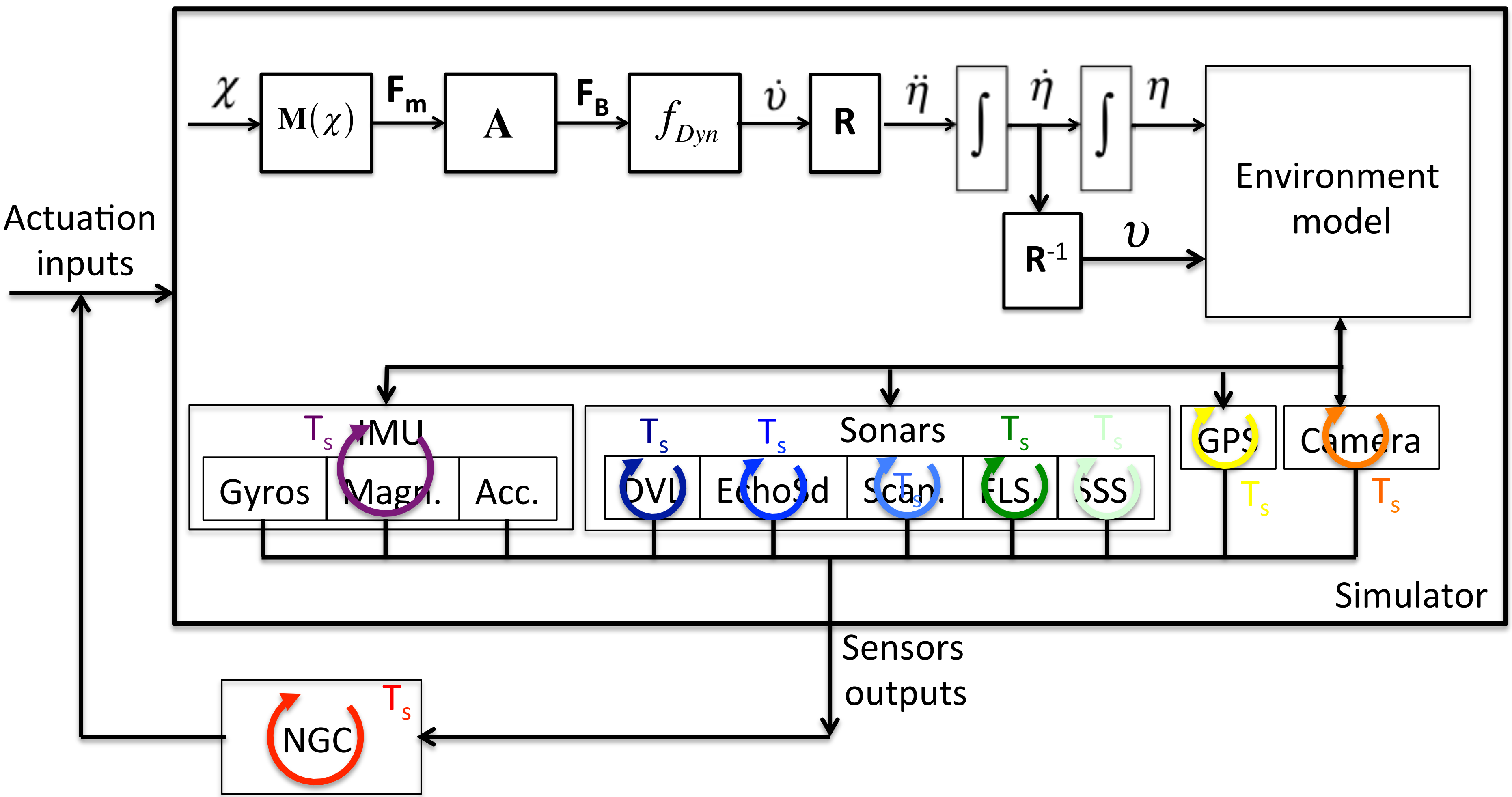
Simplify the problem considering system symmetry

Simulation



χ
$\mathbf{M}(\chi)$
$\mathbf{F_m}$
A
$\mathbf{F_B}$
f_{Dyn}
$\dot{\upsilon}$
R
$\ddot{\eta}$
$\int$
$\dot{\eta}$
$\int$
η
$\mathbf{R}^{-1}$
υ
Environment model
Actuation inputs
IMU
Gyros
Magn.
Acc.
Sonars
DVL
EchoSd
Scan.
FLS.
SSS.
GPS
Camera
Simulator
Sensors outputs

Simulation



χ
$\mathbf{M}(\chi)$
$\mathbf{F_m}$
A
$\mathbf{F_B}$
f_{Dyn}
$\dot{\upsilon}$
R
$\ddot{\eta}$
$\int$
$\dot{\eta}$
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SSS
GPS
Camera
T_s
Simulator
Sensors outputs
NGC

Open issue : Discrete Control Problem