H_∞ preview control of an active stabilizer for heart-beating surgery

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French-Israeli Workshop on Delays and Robustness
Haifa, Israel, April 3-5, 2011

Outline

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Context of beating-heart surgery

Context

- Coronary Artery Bypass Grafting (CABG): a frequent operation in the case of heart blood irrigation insufficiency
- Current most used procedure: stop the heart and implementation of an extra corporeal circulation
- CABG with heart-beating operation: reduce complications
- Use of mechanical stabilizers in order to immobilize the area of operation (ex: Octopus by Medtronic)

Limitation of current stabilizers

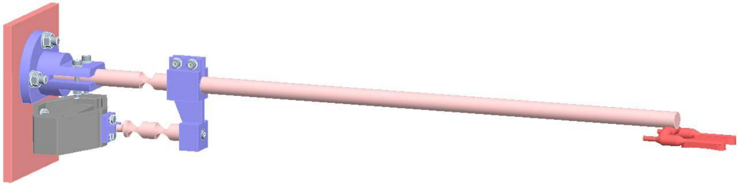
- Residual displacement about 1 mm [Cattin04]
- Required accuracy : 0.1 mm
- Insufficient of endoscopic surgery [Loisance05]

Investigated solution

Figure: Invasive stabilizer: Octopus 4.3 (Medtronic)

Figure: Endoscopic stabilizer: Octopus TE (Medtronic)

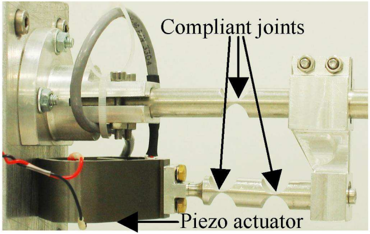
Cardiolock 1



Description

- **Beam**
  - Diameter compatible with minimally invasive surgery (10 mm diameter)
  - Sterilizable in autoclave
  - Fixed on the heart by suction
- **Actuation system**

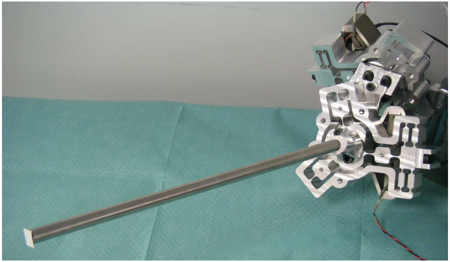
Cardiolock 1



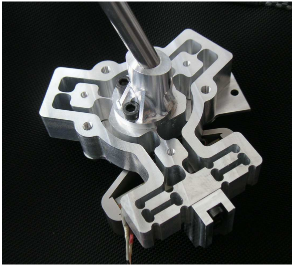
Description

- **Beam**
- **Actuation system**
  - Parallel mechanism
  - Rotating compliant joints: no backlash
  - Linear piezo actuator: high dynamics and accuracy
  - Enclosed in a sterile bag

Cardiolock 2



Full system

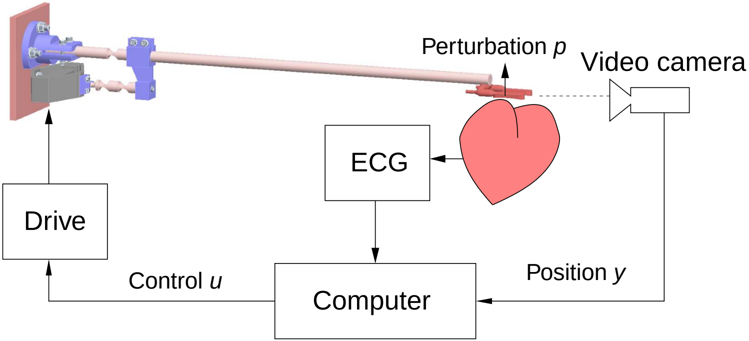


Detail on one DOF

- 2 DOF
- Each DOF is actuated by a parallel mechanism in quasi-singulaity

Outline

Cardialock under operation



- Perturbation rejection (heart beating and respiration)
- Availability of the frequencies of the heart (ECG) and respiration (artificial ventilation) for constructing a model of the perturbation

Dynamic model

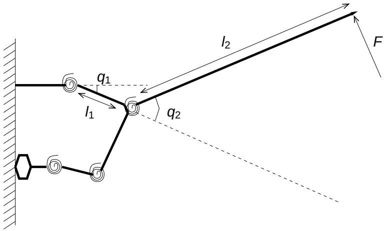


Figure: Simplified scheme with equivalent rigid deformation

Modelling

Under the PRBS assumption

- Control : $u = q_1$
- Measurement by camera : y = position of the tip of the beam

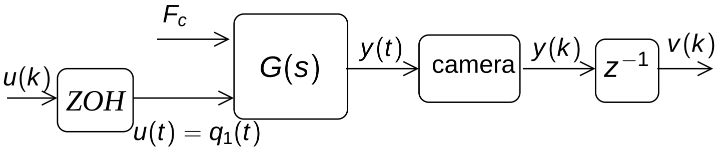


Figure: Bloc-diagram of the system

$$M_{21}\ddot{q}_1 + M_{22}\ddot{q}_2 = l_2 F_c - K_2 q_2 - f_2 \dot{q}_2 \quad (1)$$

$$q_1 = u \quad (2)$$

$$y = (l_1 + l_2) q_1 + l_2 q_2 \quad (3)$$

Flexible non-minimum phase system

Control issue

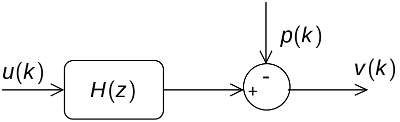


Figure: Simplified scheme for control design

Camera + ZOH equivalent to a UOH [IFAC 2008]

$$H(z) = z^{-1}\left(\frac{1 - z^{-1}}{T}\right)^2 \mathcal{Z}\mathcal{L}^{-1}\left(\frac{G_2(s)}{s^2}\right)$$

Control issue

- Rejection of an output perturbation
- Estimation of the perturbation with $\hat{p} = H(z)u - v$

Frequency response

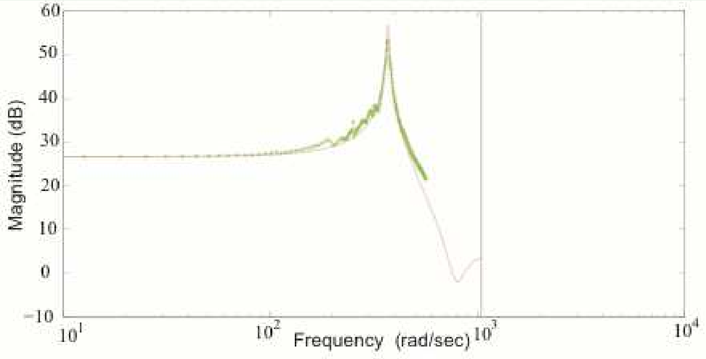


Figure: Frequency response of identified $H(z)$

Prediction of the perturbation

- Two components:
  - heart ($\mathrm{d}\phi_c/\mathrm{d}t = 2\pi f_c$ where f_c is evaluated after each ECG period)
  - ventilation ($\mathrm{d}\phi_r/\mathrm{d}t = 2\pi f_r$ where f_r is given by the ventilation system)
- Perturbation signal $p(t) = \mathcal{M}_r(t) + \mathcal{M}_c(t)$
- Ventilation component only from ventilation phase: $\mathcal{M}_r(t) = \sum_{l=1}^{n_r} a_l \sin\left(l\phi_r(t)\right) + b_l \cos\left(l\phi_r(t)\right)$
- Heart composante based on both heart and ventilation phases : $\mathcal{M}_c(t) = \mathcal{C}_c(t)(1 + \mathcal{C}_r(t))$ where
  - $\mathcal{C}_c(t) = \sum_{l=1}^{n_c} e_l \sin\left(l\phi_c(t)\right) + f_l \cos\left(l\phi_c(t)\right)$
  - $\mathcal{C}_r(t) = \sum_{l=1}^{n_r'} g_l \sin\left(l\phi_r(t)\right) + h_l \cos\left(l\phi_r(t)\right)$
- Change of variable in order to obtain a linear-parameter model ($p(t) = \sum_{l=1}^{n_\theta} \theta_l \phi(t)$) and parameter estimation with recursive mean square
- Prediction $\hat{p}(t+\delta) = \sum_{l=1}^{n_\theta} \hat{\theta}_l \, \phi(t+\delta)$

Evaluation on experimental data

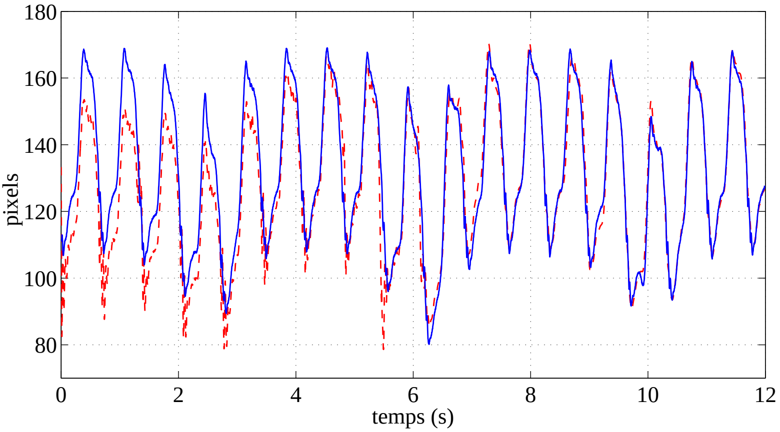


Figure: Residual displacement measured with a passive stabiliser (plain) and 3-samples ahead prediction (dashed, $T_e = 3$ ms)

Outline

Several approaches for rejection of quasi-periodic perturbation

- Dynamic output feedback
- Estimate and compensate
  - Least-square recursive estimation
  - Kalman filter
- Repetitive control (in discrete-time)
- Adaptive compensation (direct adaptation of the parameters of a perturbation model [Bodson 2001])

Simple feedback controller (synthesis in continuous time)

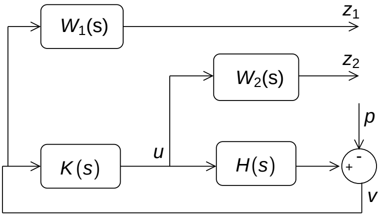


Figure: 2-blocs synthesis scheme (for tuning modulus margin, accuracy, bandwidth and roll-off)

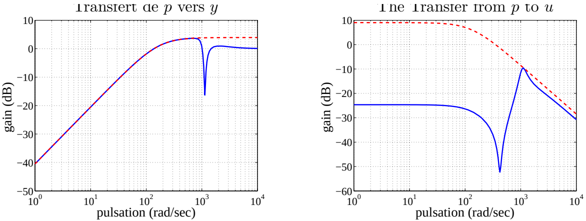
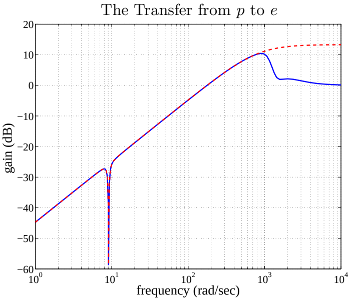
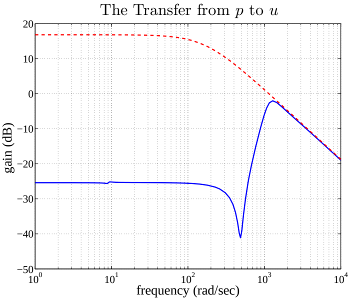


Figure: Frequency response (features: dot; system behavior: plain)

Resonant feedback controller

- $W_1(s)$ is modified with a resonant filter adapted to the cardiac frequency





2-DOF controller (feedback + feedforward)

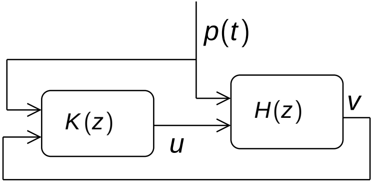


Figure: Control scheme with measured perturbation

- $K(z) = [K_1(z) \mid K_2(z)]$, $H(z) = [H_1(z) \mid H_2(z)]$
- $T_{vp}(z) = (I - H_2(z)K_2(z))^{-1}(H_1(z) + H_2(z)K_2(z))$
- Feedback $K_2(z)$ for rejection in low frequency (robust to the model errors)
- Feedforward $K_1(z)$ to enhance the rejection at higher frequency ($K_1(z) = -H_2^{-1}(z)H_1(z)$) (sensitive to the model errors)
- Restriction if $H_1(z)$ have non proper or non sable inverse (both in our case)
- Solution: synthesis of $K(z)$ in one shot (idem as an additional measurement)
- Limitation: the information comes too late for an efficient control action

Preview controller

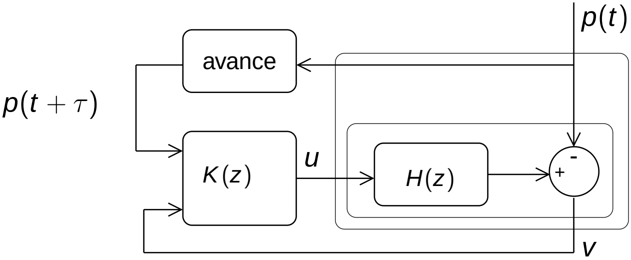


Figure: Principle of preview control

- Anticipation made possible by the prediction model
- Controller synthesis in one shot
- Similitude with predictive control: requires to know in advance the future samples of the exogenous signal (i.e. reference or perturbation)
- Equivalent for reference tracking

Full control scheme

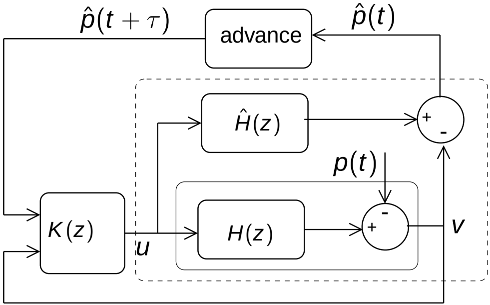


Figure: Control scheme with estimation of the perturbation

Synthesis scheme

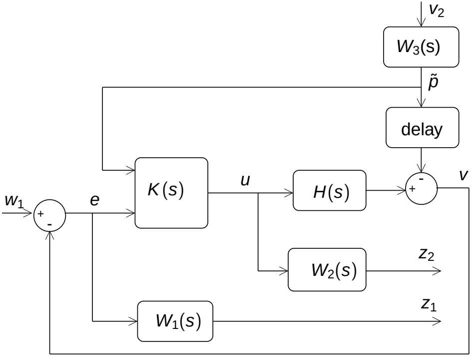


Figure: Synthesis scheme for the 2-DOF controller allowing to tune separately the feedback and feedforward effects ($\tilde{p}(t) = e^{\tau s}p(t)$)

- Synthesis in continuous-time (continuous-to-discrete conversion with the bilinear transform)
- Pade approximation of the delay
- Advance from the prediction model

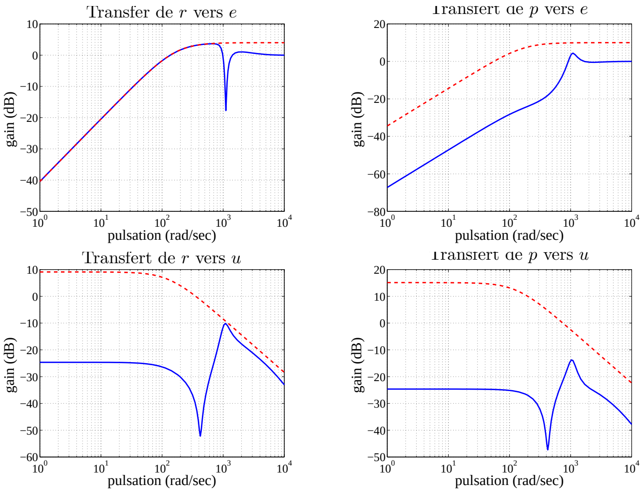
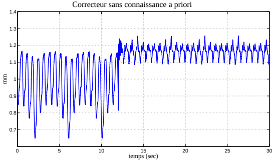


Figure: Frequency response with the 2-DOF preview controller (features: dots; realized system: plain)

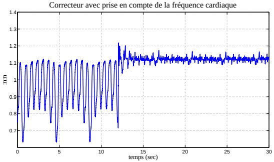
Laboratory experimental setup

- Heart movement emulated by a pan-tilt robot

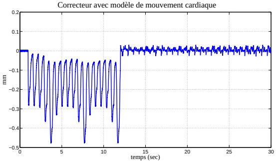
Experimental results



Simple feedback



Resonant feedback



2-DOF with preview

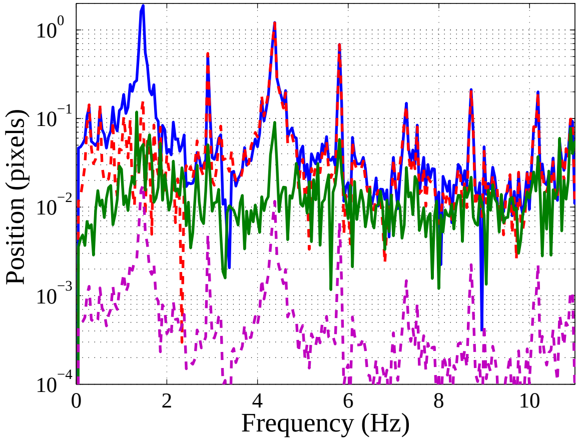
- In-vivo tests were also made

Evaluation in simulation with experimental data

Control method	RMS displacement (pixel)
No control	22.3
Simple feedback	2,57
Resonant feedback	1,69
2-DOF with preview with perfect prediction	0,064
2-DOF with preview with estimated prediction	1,21

Table: Residual displacement obtained with the nominal model (prediction made with $n_c = 10$ and $n_r = n'_r = 4$)

Residual movement frequency analysis



blue: simple feedback; red: resonant feedback; purple: 2-DOF with preview with perfect prediction; green: 2-DOF with preview with estimated prediction

Outline

Uncertain model

Robustness issue

Modification of the system behavior when in contact with the heart

Interaction model

$$F = F_c - k_c\, y - f_c\, k\dot{y} - m_c\, \ddot{y} \tag{4}$$

- F_c: exogenous perturbation
- Nominal values: $m_c = 2$ g, $K_c = 250$ N/m and $f_c = 0.1$ N.s/m
- Consider variations from 0 à 200 %

Uncertain model

μ-analysis context

- Constants uncertains parameters
- LFR model
- Use of a performance criterion
- Robust if $\mu < 1$

Simple feedback control

LFR model (stability + performance)

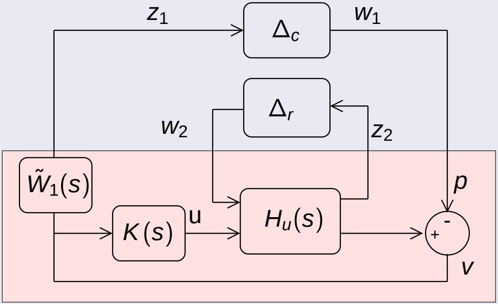


Figure: Structure du modèle LFR incertain

Δ_c real diagonal; Δ_r full complex

Repetition index of the uncertain parameters

Parameter	Direct	Reduction	Robust toolbox
m_c	9	3	1
K_c	3	2	1
f_c	3	1	1

Table: Repetition index of the uncertain parameters of the LFR model obtained with different methods (Direct and Reduction: with LFR toolbox

μ plot

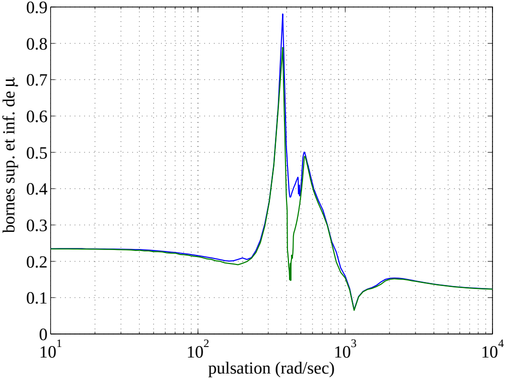


Figure: Structured singular value

$\rightarrow$ $\mu < 1$: robust to the considered uncertainties

2-DOF preview control

- Non causal model $T_{yp}(s) = \mathrm{lft}(G(s), e^{\tau s})$ that cannot be factorized (i.e. $T_{yp}(s) = e^{\tau_1 s} G_1(s) e^{\tau_2 s}$) $\rightarrow$ usual tools cannot be used
- Evaluation in simulation with $p_k = \rho\, p_{k0}$ where p_{k0} is the nominal value and $\rho \in [0\,;2]$

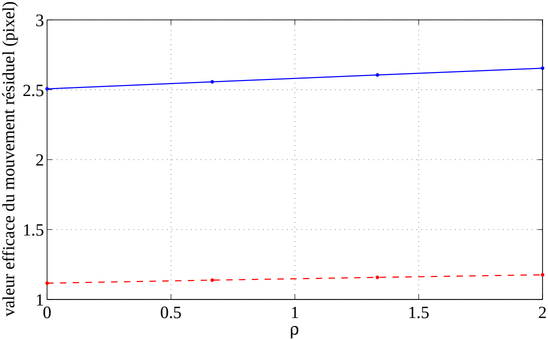


Figure: Variation of the residual motion with respect to the parameter value ρ (plain: feedback control; dashed: preview control)

Outline

Conclusion

- Simple and efficient procedure for synthesis of preview H_∞ control
- Improvement thanks to the prediction of the pertuabation
- Obtained accuracy in accordance with the requirements for heart-beating surgery

Future work

- Robustness analysis for the 2-DOF prevew controller with estimation
- Evaluation of Cardiolock 2
- Comparison with GPC