Control Optimization for KAGRA VIS

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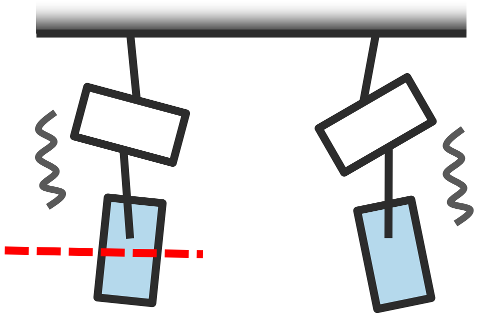
Target

- Listen to me

What Is “Optimum”

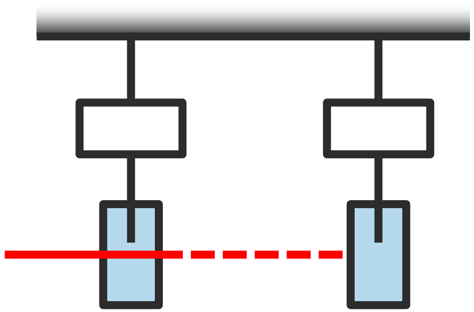
DEPENDS ON SITUATIONS!!

Optimum for Suspension Control



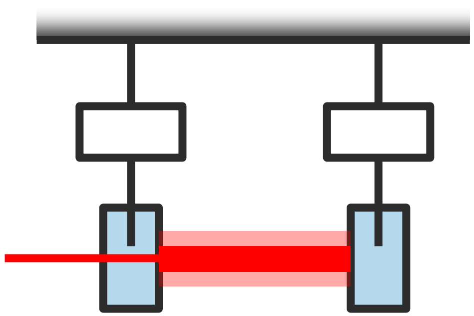
Calm-down phase

Damp resonant modes to get optical signals



Lock acquisition phase

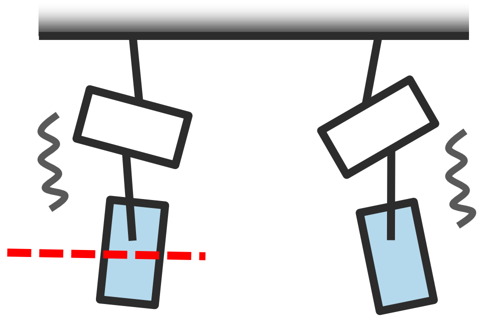
Achieve interferometer to be locked smoothly



Observation phase

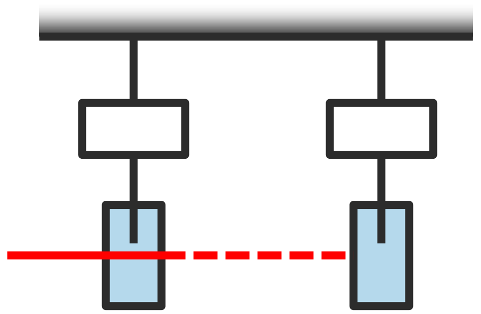
Keep interferometer stably locked with low control noise @ > 10 Hz

Requirements for Suspension Control



Calm-down phase

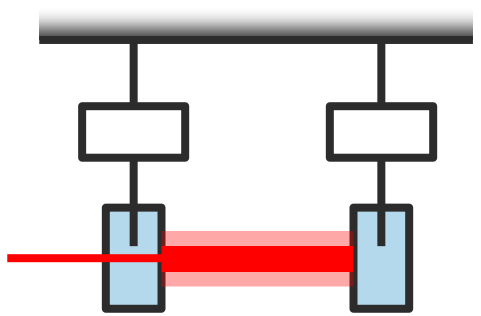
1/*e* decay time < 60 sec.



Lock acquisition phase

RMS velocity < 0.5 um/sec

RMS angle < 0.2 urad



Observation phase

Control noise < 1×10^{-19} m/Hz$^{1/2}$ @ 10 Hz

Long-term drift < (2nm), 0.2 urad /day

What Is Optimization?

A problem to find a parameter set $\boldsymbol{x} = \{x_1,\ x_2,\ \ldots,\ x_n\}$

which **minimize** or **maximize** the objective function $f(\boldsymbol{x})$

such as $f(\boldsymbol{x}) : \mathbb{R}^n \to \mathbb{R}$.

To state this problem,

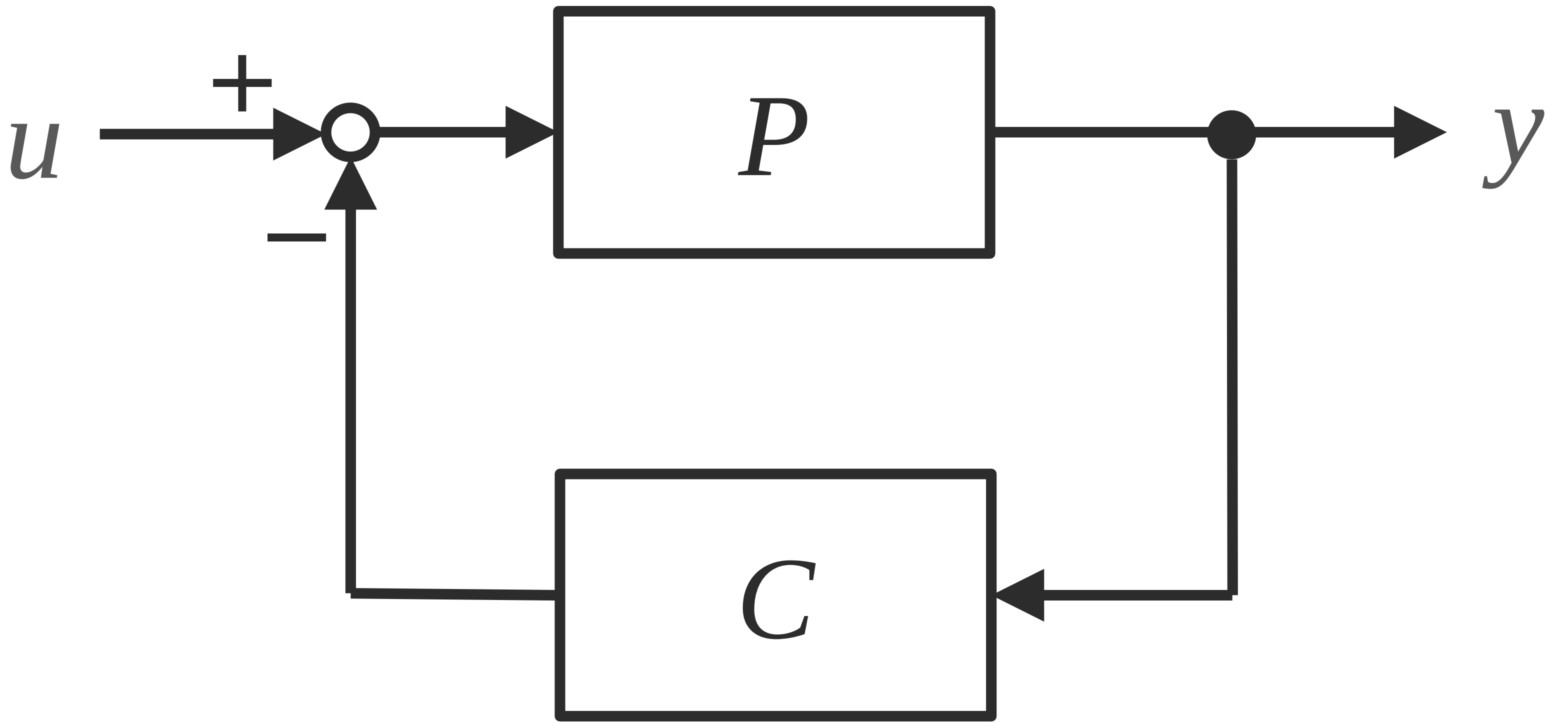
$$\min_{\boldsymbol{x}} f(\boldsymbol{x}),$$

subject to

$$g_i(\boldsymbol{x}) \leq 0, \quad i = 1, \ldots, m$$

$$h_i(\boldsymbol{x}) = 0, \quad i = 1, \ldots, p$$

Optimization in Feedback Control



To design a controller C

to realize "optimal" behavior of the plant P

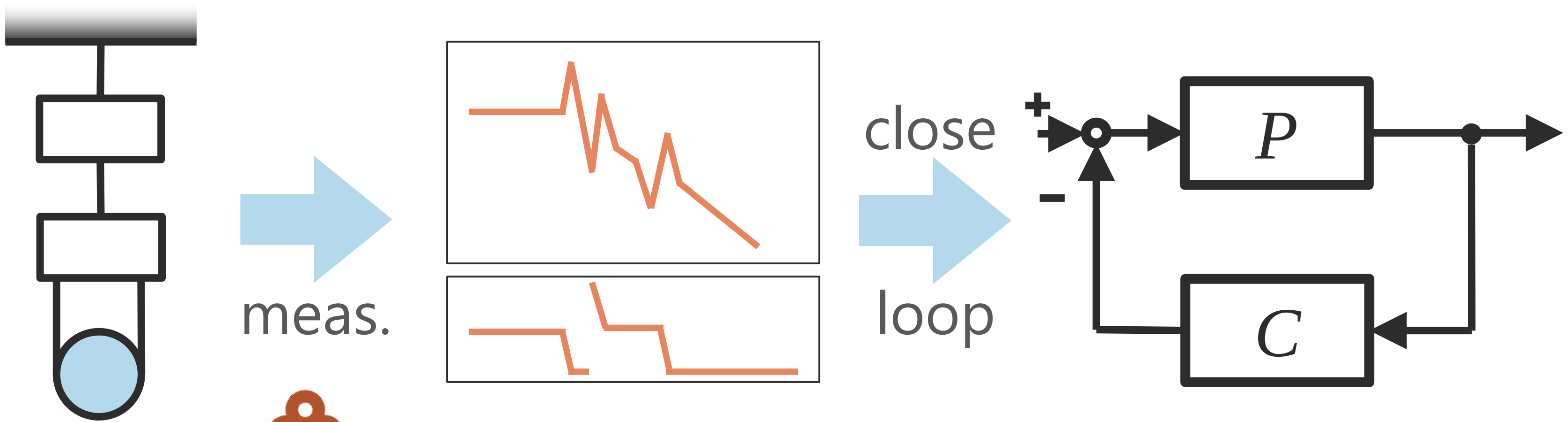
How to Realize Optimal Controller?

To set an objective function $f(\boldsymbol{x})$, one needs an analytical model which represents behavior of the plant

↓

Model-based control

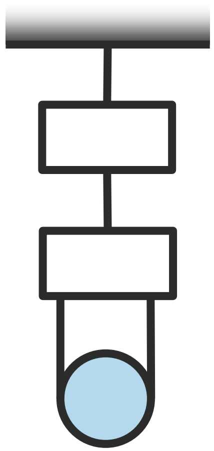
Controller Design in Classical



Transfer function

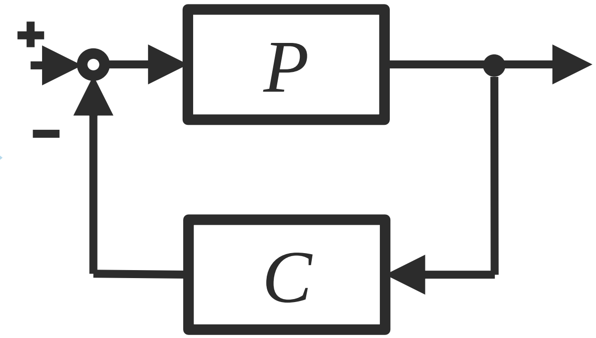
- Single-input single-output (SISO)
- Frequency domain
- Linear, time-invariant

Controller Design in Model-based



Modeling

$$\dot{\boldsymbol{x}} = A\boldsymbol{x} + B\boldsymbol{u}$$
$$\boldsymbol{y} = C\boldsymbol{x} + D\boldsymbol{u}$$



State-space model

- Multi-input multi-output (MIMO)
- Time domain
- (non-linear, time-variant system)

State-space (SS) Model

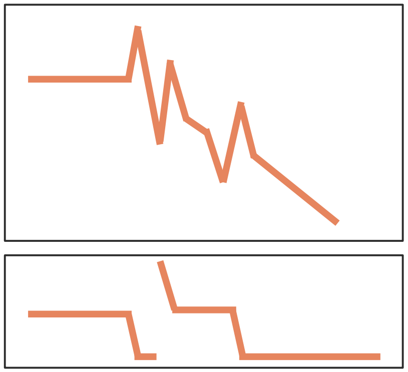
A mathematical model of a physical system as a set of input, output and state variables related by **first-order differential equation**,

$$\dot{\boldsymbol{x}}(t) = A\boldsymbol{x}(t) + B\boldsymbol{u}(t),$$
$$\boldsymbol{y}(t) = C\boldsymbol{x}(t) + D\boldsymbol{u}(t).$$

Here,

$\boldsymbol{x} \in \mathbb{R}^n$	: state variables	A	: system matrix $(n \times n)$
$\boldsymbol{u} \in \mathbb{R}^m$	: system inputs	B	: input matrix $(n \times m)$
$\boldsymbol{y} \in \mathbb{R}^p$	: system outputs	C	: observation matrix $(n \times p)$

Stability of System



$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

Transfer function

Stable if the real part of all poles is < 0

State-space

Stable if the real part of all eigenvalues of the system matrix A is < 0

Poles in TF ⟷ Eigenvalues of A

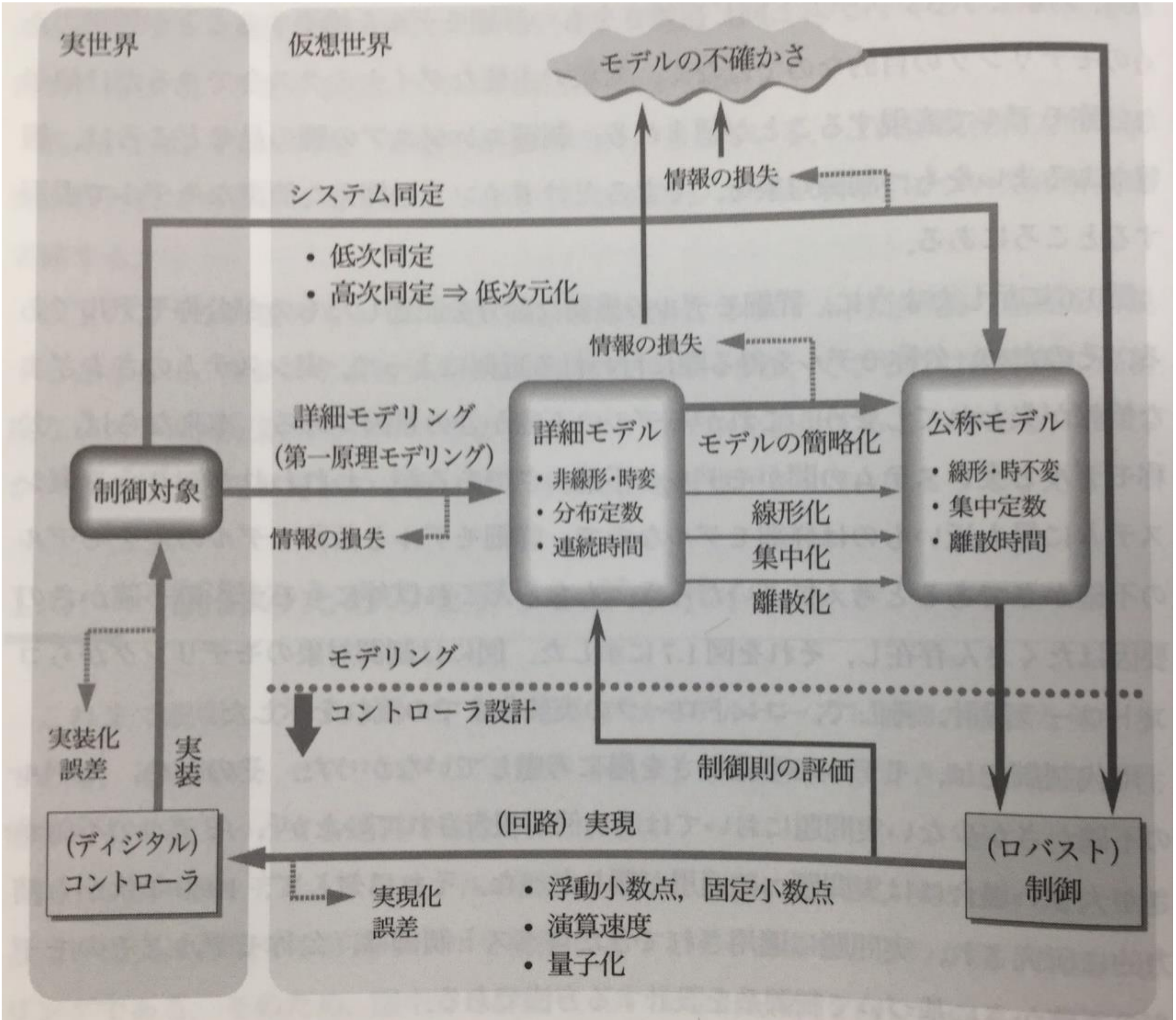


図 1.7　モデリングから制御系設計までの流れ（実世界と仮想世界）

S. Adachi『システム同定の基礎』(2009)

(Full) State Feedback

If we set the system input as

$$\boldsymbol{u}(t) = -F\boldsymbol{x}(t),$$

(BLANK)

Observability and Controllability

(BLANK)

Kalman Filter

(BLANK)

Linear Quadratic Gaussian Regulator

評価関数

$$J = \sum_{i=1}^{n} q_i J_{x_i} + \sum_{j=1}^{p} r_j J_{u_j} = \int_0^{\infty} \left(\sum_{i=1}^{n} q_i x_i(t)^2 + \sum_{i=1}^{n} r_j u_j(t)^2 \right) dt$$

評価関数の重み $q_i \geq 0,\ r_j > 0$ の役割

- $q_i \geq 0$ を大きくすれば，“状態 $x_i(t)$ の 0 への収束の速さ（J_{x_i} を小さくすること）”を重視することになる。
- $r_j > 0$ を大きくすれば，“操作量 $u_j(t)$ が過大でないこと（J_{u_j} を小さくすること）”を重視することになる。

My Scope

To implement optimal hierarchical controller with Kalman filter to Type-A control

Feasibility in control test of Type-A Tower @ETMX

Control Phase	Simulation	Measurement
Calm-down	○	○
Lock acquisition	○	×
Observation	○	×

Problem on Implementation

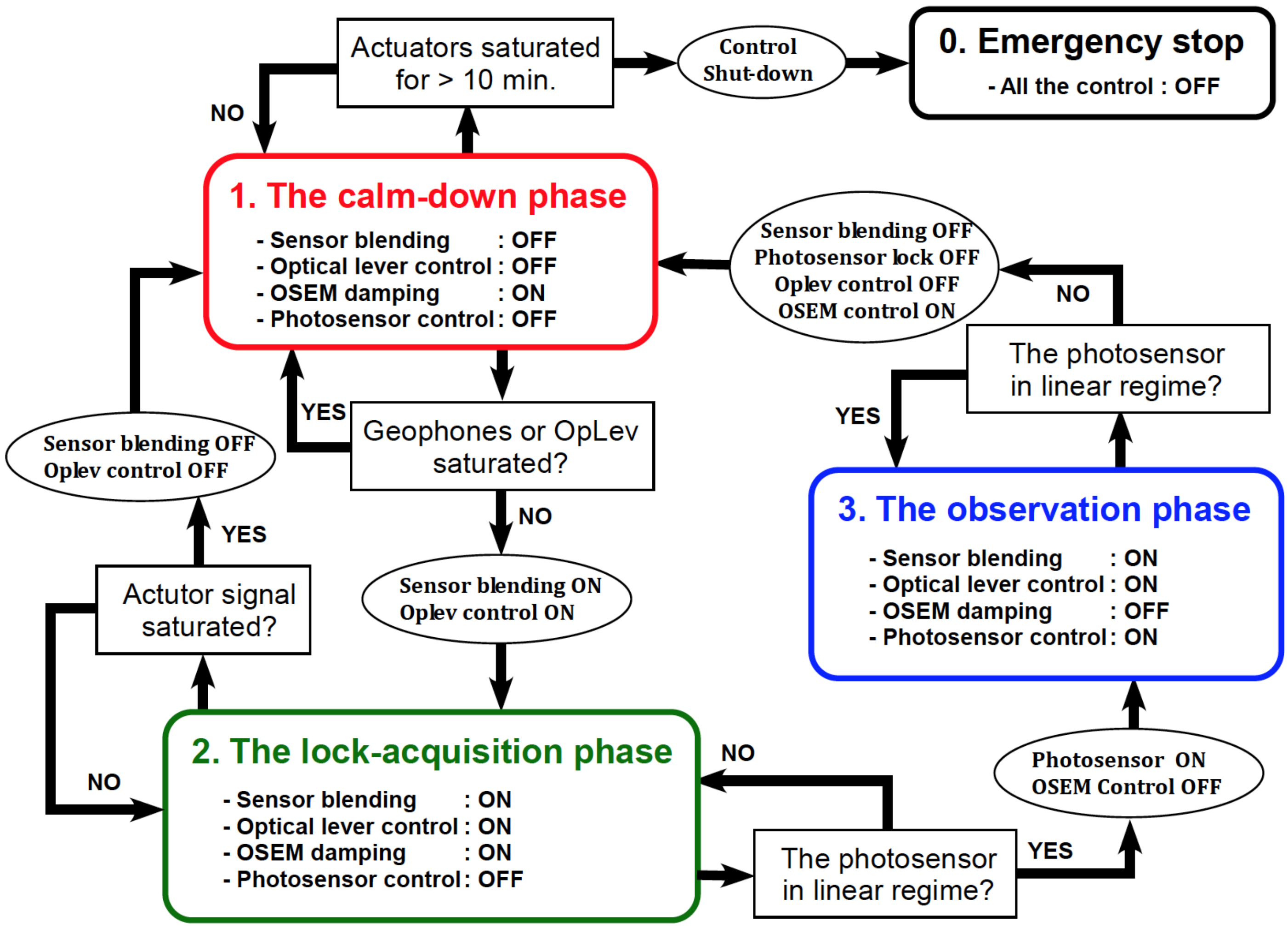
- Current KAGRA scheme: decoupling control
  - decouples sensor signals into each DoF of interest
  - implements servo filters in each mass-wise DoF
- New scheme: MIMO optimal control
  - has one MIMO controller

References

[1] JGW-P1504155: T. Sekiguchi, Ph.D. Thesis

[2] G. Vajente

Appendix



Actuators saturated for > 10 min.
Control Shut-down
0. Emergency stop
- All the control : OFF
NO
1. The calm-down phase
- Sensor blending : OFF
- Optical lever control : OFF
- OSEM damping : ON
- Photosensor control : OFF
Sensor blending OFF
Photosensor lock OFF
Oplev control OFF
OSEM control ON
NO
The photosensor in linear regime?
YES
YES
Geophones or OpLev saturated?
Sensor blending OFF
Oplev control OFF
NO
YES
3. The observation phase
- Sensor blending : ON
- Optical lever control : ON
- OSEM damping : OFF
- Photosensor control : ON
Actutor signal saturated?
Sensor blending ON
Oplev control ON
NO
2. The lock-acquisition phase
- Sensor blending : ON
- Optical lever control : ON
- OSEM damping : ON
- Photosensor control : OFF
NO
Photosensor ON
OSEM Control OFF
YES
The photosensor in linear regime?