Modeling and Control of Tower Crane Motions

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Crane's accidents

Cranes

are widely used to transport heavy loads in shipyards, factories and construction sites.

Hazards associated with operating or working near cranes leading to injuries and deaths of workers (1 in 10 construction workers are injured annually).

- Many accidents happened due to improper operation of the crane, not following manufacturer instructions, poor control of load dynamic behaviour.
- Also, wind related accidents are due to the operator not following proper shut-down procedures.
- When the oscillations of the payload passed the critical limit :
  1. The operator must damp the oscillations.
  2. or halt the operation till natural damping occurs.

  Both options are time consuming and reduce efficiency of the process.

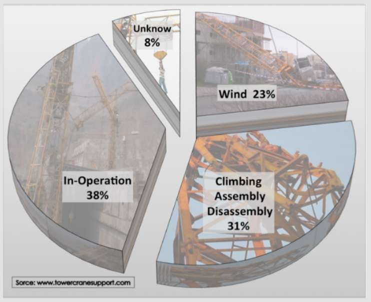

FIGURE 1 – Tower Crane Accidents' Statistics

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The proposed solution : Automated Tower Cranes

Automated Tower Cranes

Objective :

1. Precise trajectory tracking.
2. Reduced transfer time.
3. Elimination of the payload oscillations.
4. Regardless to the working conditions (wind).

FIGURE 1 – Tower Crane in Construction Site [1]

- Safety issues on construction sites are no longer a concern.
- Raising the efficiency and productivity of the construction process.

Process Automation Evolution

Level 5

Autonomous Intelligent

Adaptive, self learning and intuitive systems with decision making capabilities process **without human intervention** while handling all tasks including fail safe and weather conditions

Level 4

Intelligent Process Automation

The automated system controls all operational and tactical decisions **under human supervision** by identifying pattern of unstructured data, image recognition, learning and making predictions.

Level 3

Advanced Process Automation

Semi-structured data processing through predefined algorithms to handle dynamic processes. **Human takes over when necessary**.

Level 2

Basic Process Automation

Labor-intensive repetitive tasks are replicated following predetermined path while handle structured data and standardized processes. **High level of human intervention and operating.**

Level 1

Assisted Process Automation

Humans are in full control but alerted with conditions, environment and obstruction. No control actions taken by the system.

Level 0

No Automation

All tasks are carried out by the labors manually.

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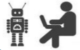

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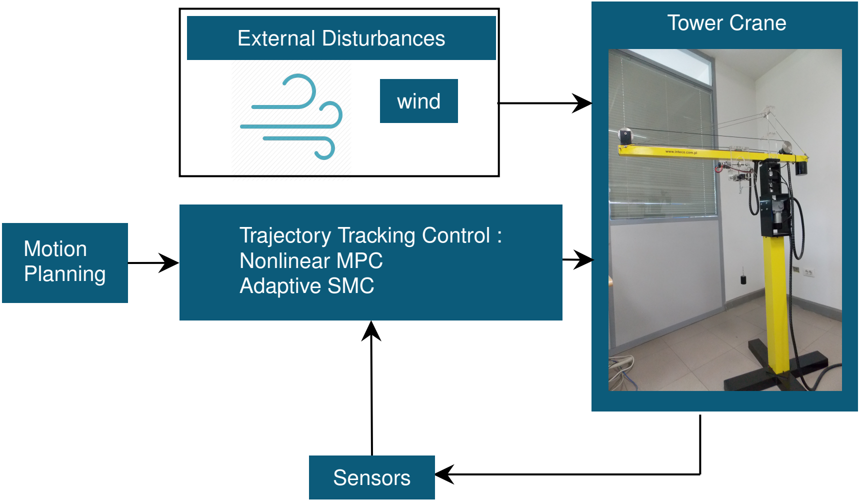
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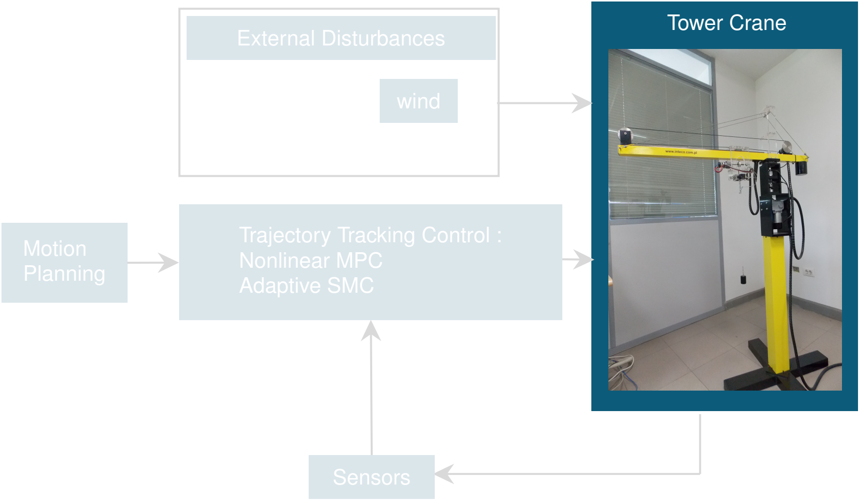
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Tower Crane System

- The Tower Crane is **modeled** as a five degree of freedom robotic arm : Trolley, Jib, Alpha, Beta and Cable.
- A highly nonlinear underactuated MIMO system. Hence, controlling such a system is hard compared to a fully actuated system since it has only two inputs for obtaining four outputs.

FIGURE 2 – Lab sized tower crane

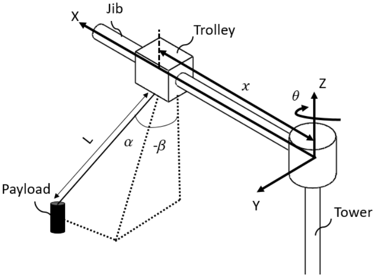

FIGURE 3 – Schematic Representations of Tower Cranes

Dynamics

The nonlinear model equations was based on Lagrangian method :

$$\underbrace{M(q)\,\ddot{q}}_{\text{inertia matrix}} + \underbrace{b(q,\dot{q})}_{\text{Centrifugal and damping elements}} + \underbrace{g(q)}_{\text{Gravitational forces}} = \underbrace{F}_{\text{Motor's inputs}}$$

The coupling between the Degrees of freedom is considered.
Including the coupling between the rotation of the jib and the payload oscillations, that occurs due to :

- Coriolis acceleration

$$\vec{a}_p = \vec{a}_o + \frac{{}^b d^2}{dt^2}\vec{r} + 2\vec{\omega}_{ib} \times \frac{{}^b d}{dt}\vec{r} + \vec{\alpha}_{ib} \times \vec{r} + \vec{\omega}_{ib} \times (\vec{\omega}_{ib} \times \vec{r})$$

- Centripetal acceleration

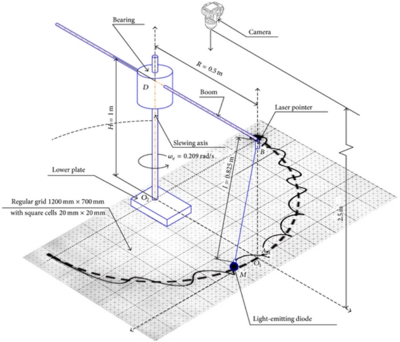

FIGURE 4 – Double Pendulum System [2]

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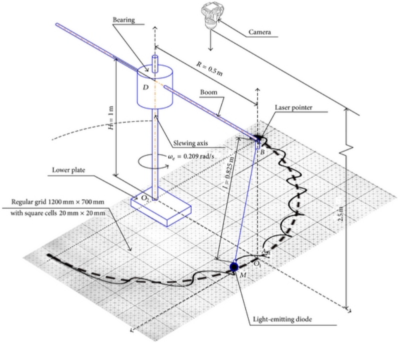
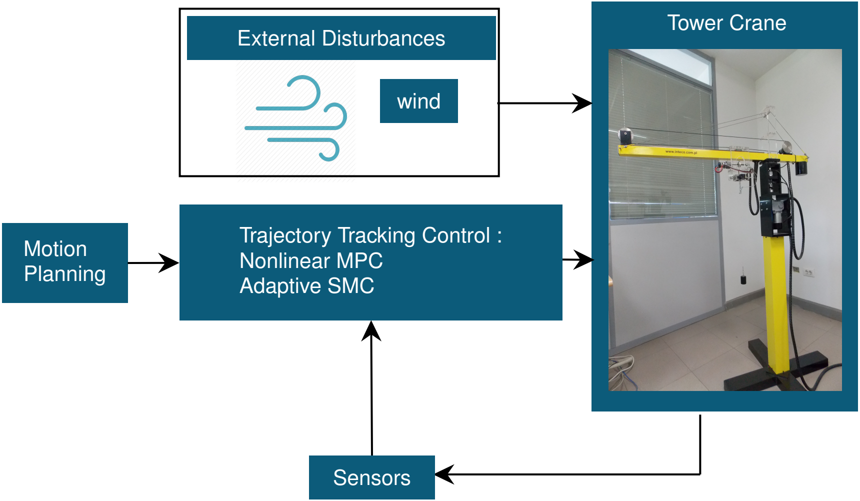


FIGURE 4 – Double Pendulum System [2]

Framework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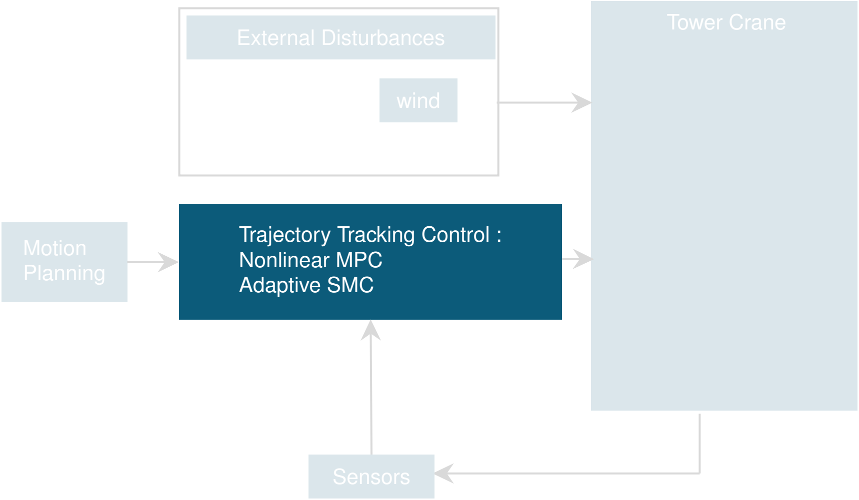
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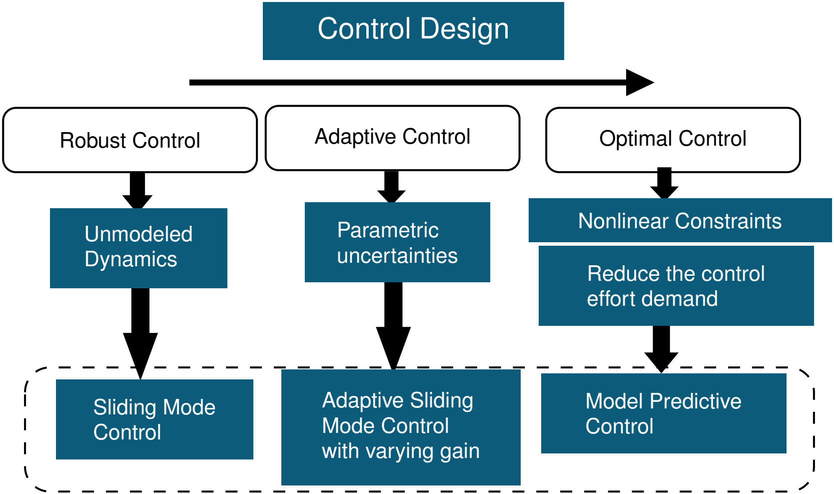
Proposed Controllers



Phases of Sliding Mode Technique

- 1^{st} phase : reaching phase where states are moving from initial position to the sliding surface in finite time.
- 2^{nd} phase : sliding phase : the states slide on the surface till it reach its desired operating point and stays there using Lyapunov theory.

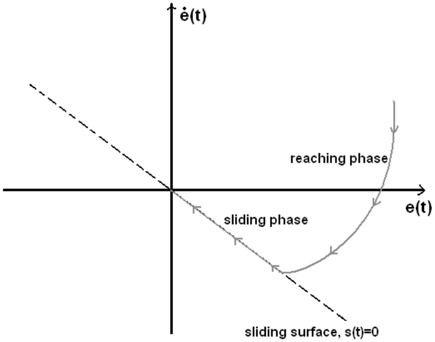


FIGURE 5 – Sliding Model Control [3]

Sliding Mode Control Procedure

Sliding Variable

Transform the system from n^{th} order to 1^{st} order :

$$s = (\frac{d}{dt} + \lambda)^{n-1}\tilde{x} = \dot{\tilde{x}} + \lambda\tilde{x}$$

e_1 and e_2 are actuated and unactuated states tracking errors.

$$\text{Given that } s = 0 : \qquad \dot{\tilde{x}} = -\lambda\tilde{x} \quad \equiv \quad \tilde{x}(t) = \tilde{x}(0)e^{-\lambda t}$$

when λ is a positive value, the states tend to zero exponentially.

Derivative of the sliding surface

$$\dot{s} = f + u + \lambda\dot{x}$$

Discontinuous controller will be designed as follows :

$$u = \underbrace{-\hat{f} - \lambda\dot{x}}_{\substack{\text{feedback controller} \\ \text{nominal part}}}$$

f is real system dynamics and $\hat{f}$ is the estimated system dynamics based on the nonlinear dynamical model.

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Derivative of the sliding surface

$$\dot{s} = f + u + \lambda\dot{x} = f - \hat{f} - Ksgn(s)$$

Discontinuous controller will be designed as follows :

$$u = \underbrace{-\hat{f} - \lambda\dot{x}}_{\substack{\text{feedback controller}\\ \text{nominal part}}} \underbrace{- Ksgn(s)}_{\substack{\text{corrective}\\ \text{term}}}$$

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Stability Analysis

Lyapunov positive definite function

$$V = \frac{1}{2}s^2$$

u is substituted in derivative of Lyapunov function to get :

$$\dot{V} = s\dot{s} = s(f - \hat{f} - Ksgn(s))$$

using $s.sgn(s) = |s|$.

$$\dot{V} = s(f - \hat{f}) - K|s|$$

The model uncertainties with its constant upper bound given by :

$$|f - \hat{f}| \leq F = \text{constant}$$

$$\dot{V} \leq |f - \hat{f}||s| - K|s|$$
$$\dot{V} \leq (F - K)|s| \qquad \text{where, } K = F + \eta$$
$$\dot{V} \leq -\eta|s| < 0$$

Therefore, $s \to 0$ as $t \to \infty$ which is Globally Asymptotically stable when $\eta > 0$.

Adaptive Sliding Mode Control

An adaptation law is added to calculate the varying parameters, to be used by the controller.

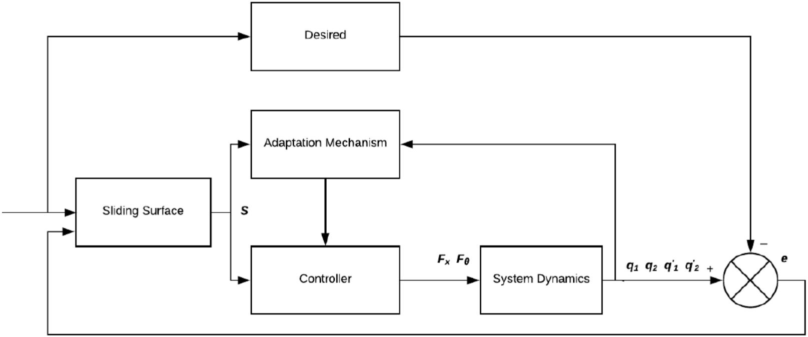


FIGURE 6 – ASMC Procedure

Nonlinear Model Predictive Control (NMPC)

Also named receding horizon control, relies on :

- Solving an Optimal Control Problem (OCP) at each sampling instant.
- Applying the first part of the optimal control input to the system.
- The optimization horizon is shifted forward and the OCP is solved again with the actual (measured) system states as initial conditions [4]

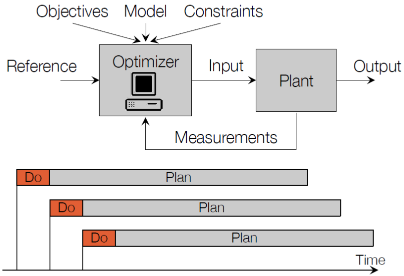


FIGURE 7 – MPC Procedure [5]

FIGURE 8 – chess [6]

Optimal Control Problem Formulation

- Model

$$x(k+1) = f_k(x(k), u(k))$$

  $x(k)$ is the state vector, and $u(k)$ is the control input.
- Constraints $(h(x(k), u(k)) \leq 0)$:
  - **Physical constraints** (i.e. limitations) on the states and/or inputs.
  - Performance constraint.
  - Safety constraint

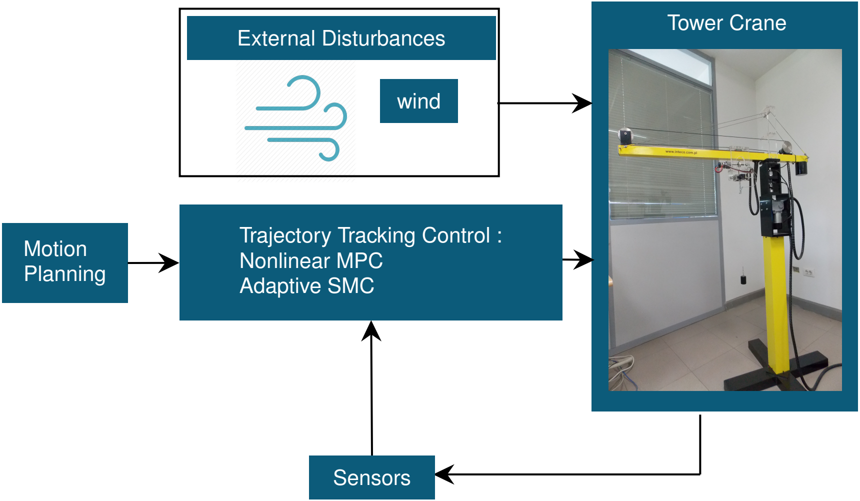
Performance Objective

The performance of a system is evaluated quantitatively, the designer selects a performance objective.
An optimal control is defined to minimize the performance objective.

$$J^*_{0\leftarrow N} = \underbrace{\min x_N^T\, P\, x_N}_{\text{Terminal Cost}} + \underbrace{\sum_{k=0}^{N-1} x_k^T\, Q\, x_k + u_k^T\, R\, u_k}_{\text{Stage Cost}}$$

where N is the time horizon, the weighting matrices are P, Q and R .

Framework



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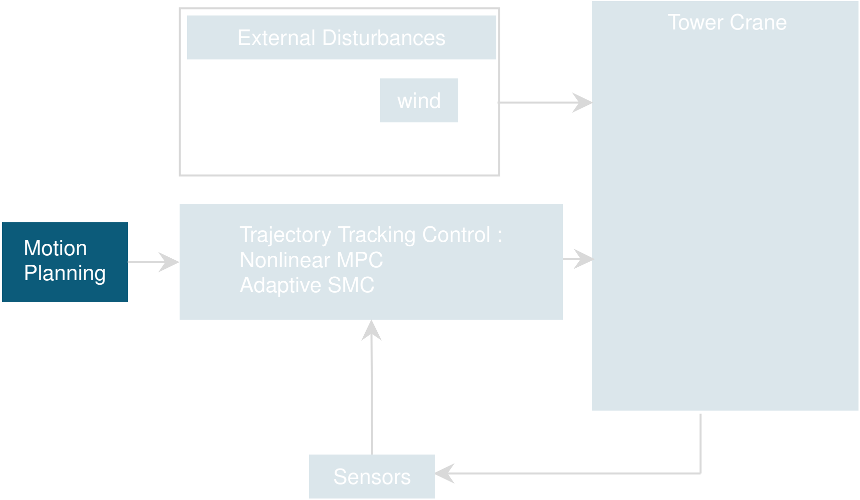
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Construction Site Simulation

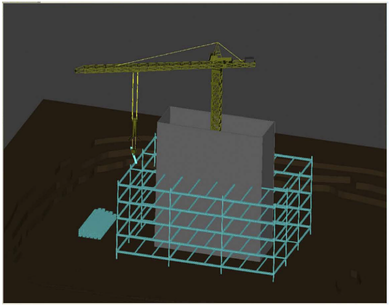


FIGURE 9 – PathPalnning [7]

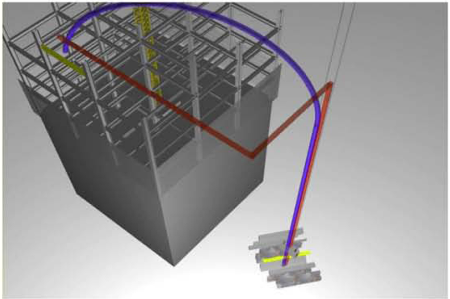


FIGURE 10 – Smoother Path [7]

- The high dynamic characteristics of construction site conditions often require re-planning in real time the crane's path to ensure safety and efficiency.
- Any unpredicted objects or other conflicts related to the operations of the cranes on site should be detected and tracked in real time.

Technique For Motion Planning

The crane model is transferred between work space (real world space) into the reduced high-dimensional space as the configuration space (C-space).

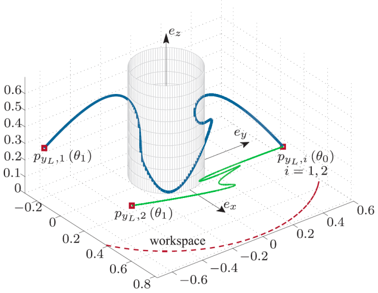


FIGURE 11 – Wspace [8]

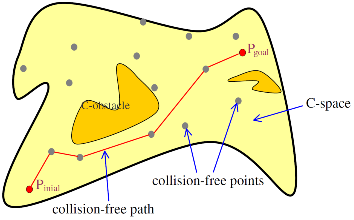
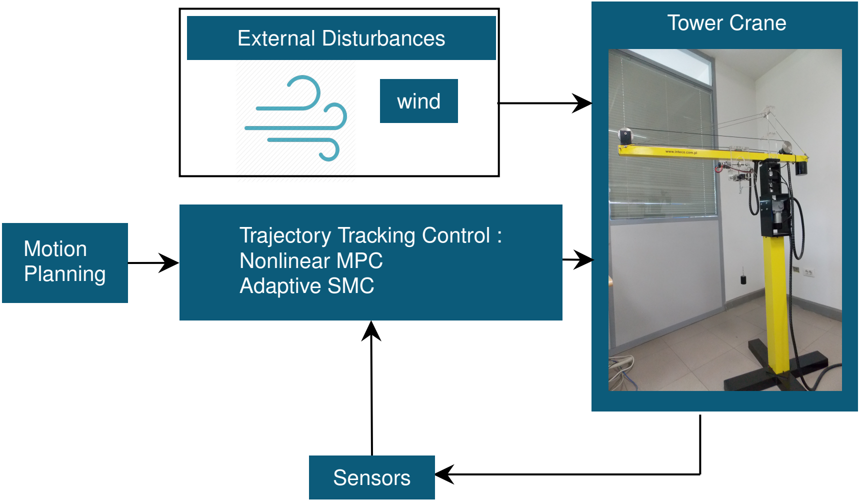


FIGURE 12 – Cspace [9]

C-obstacle : is an area in which the crane is not allowed to move, due to the collision with obstacles or the crane itself (self-collision).

- The first part focused only on finding a collision free path efficiently.
- The second part focuses on refining and optimizing the path for better crane operations.

Framework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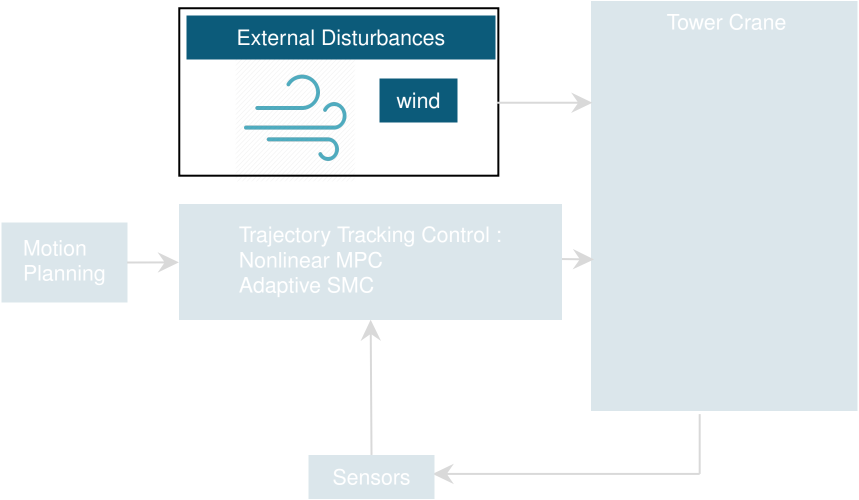

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Fuzzy Logic Controllers

An intelligent control system, learning from experience that mainly apply knowledge to manipulate the environment.

- PID Control : IF temperature $>$ 25 THEN turn A/C ON (24.9 won't be accepted).
- Fuzzy Control : IF temperature is HOT THEN turn A/C ON (depends on circumstances)

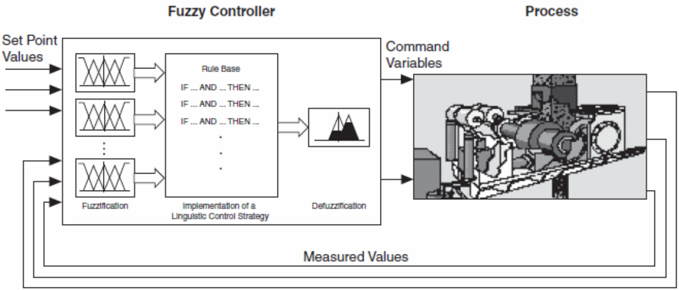
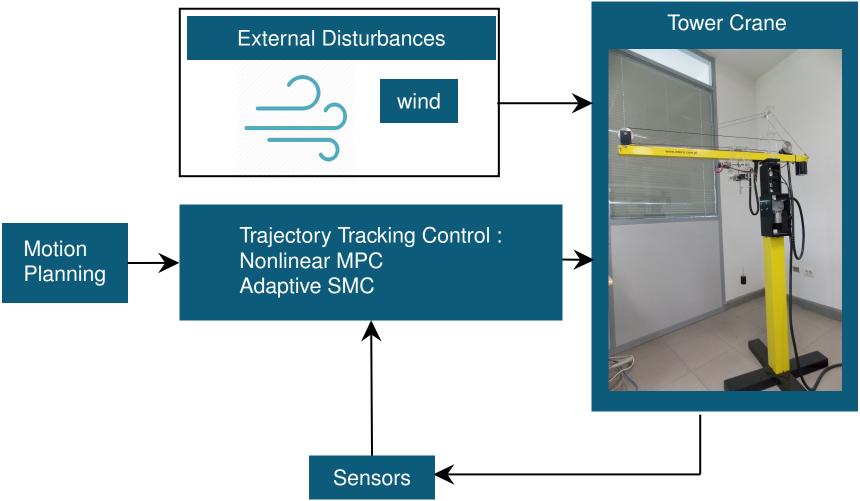


FIGURE 13 – Fuzzy Logic Toolkit From National Instruments

Takagi Sugeno-Fuzzy Observer

The external disturbances such as wind are estimated.

Framework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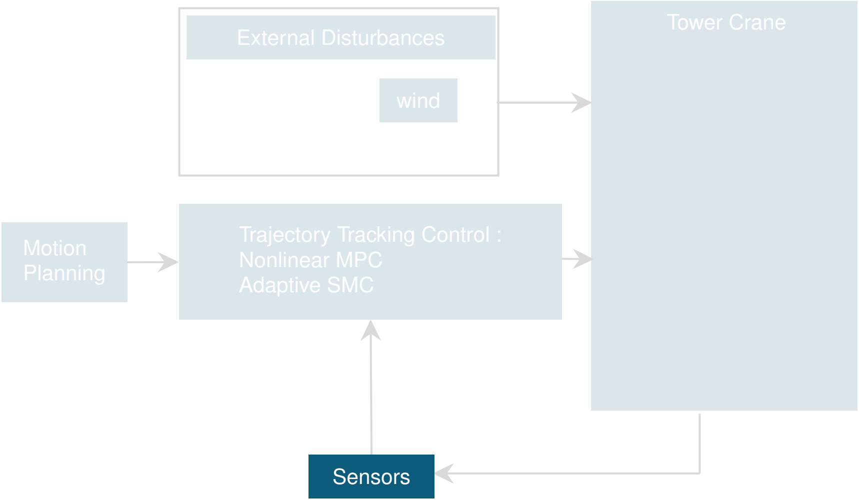
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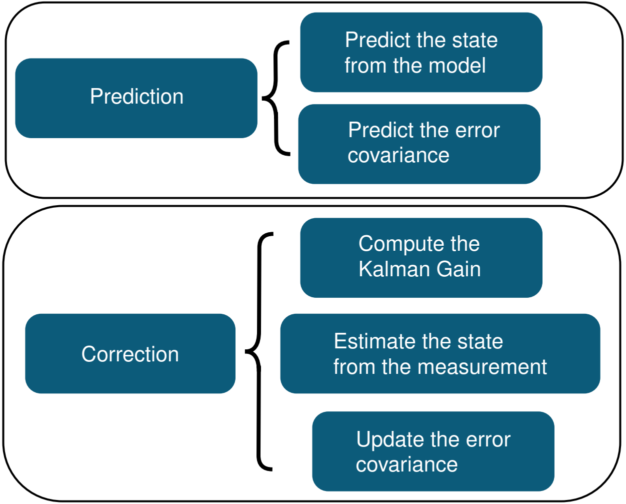
Estimators

- The states are measured using encoders.
- The unmeasured states such as velocities will be estimated using **extended Kalman filter**.



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- It is crucial to properly suppress the oscillations of the payload to avoid dangerous situations.
- Also, the rejection of external forces induced by wind.
- The efficiency of the controllers are validated experimentally on a laboratory tower crane.
- ASMC is used to handle system's uncertainties.
- The MPC controller is used taking into account the system constraints while minimizing the energy consumption.
- A collision free path is to be calculated in real time for the load to follow.

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Any Questions？
Thank you