# A Distributed Laguerre-based Model Predictive Control Scheme for Path Planning and Obstacle Avoidance with Resilience to Security-related Events

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## Model Predictive Control

**Key Part:** Uses a Model of the System to Predict and Optimise the Future Performance

**Some Applications:**
- Path Planning/Obstacle Avoidance
- Optimising Energy Usage/Generate
- Distributed/Decentralised Control
- Robust/Stochastic Control (Handling Uncertainty)
- Adaptive and Fault Tolerant Control

**Advantages:**
- Ability to Anticipate Future Events
- Non-reactive control -> Smoother Control Actions
- Handling Time-Delays, Nonlinear Dynamics and Constraints

**Disadvantages/Challenges:**
- Requires a relatively accurate model of the system
- Computational burden -> Impacts real-time capabilities

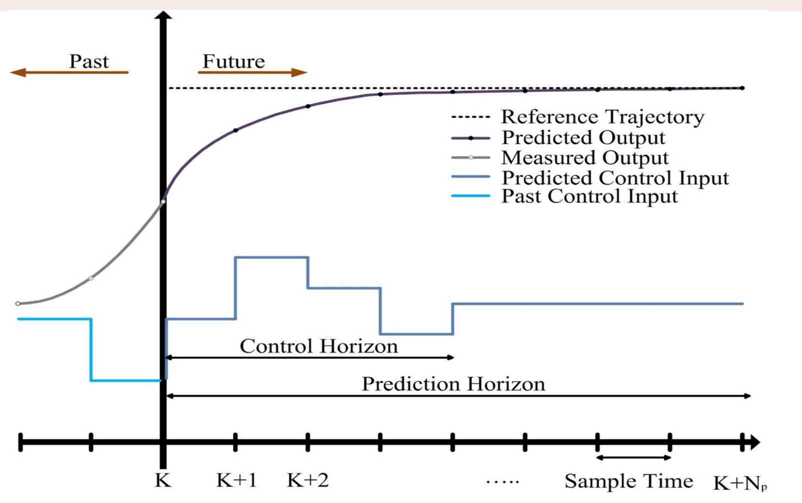

Figure 1: Predictive framework taken from [1]

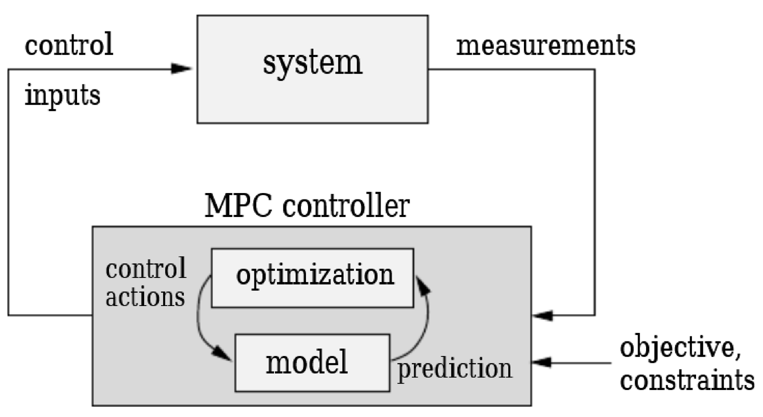

Figure 2: Predictive Control Loop taken from [2]

## Path Planning and Obstacle Avoidance for Autonomous Vehicles

**Two Common Methods:**
- Potential Fields (Preferred)
- Nonlinear Constraints

$$P = \frac{k_{pot}}{d_k - d_{min}} \quad \text{vs} \quad d_k \geq d_{min}$$

**Advantages of Potential Field:**
- Smoothness
- Reduced Computational Burden
- Scalability

**Disadvantages of Potential Field:**
- Suboptimal w.r.t. Nonlinear Constraints

**Other Applications to Path Planning:**
- Secure Communications via Physical-layer

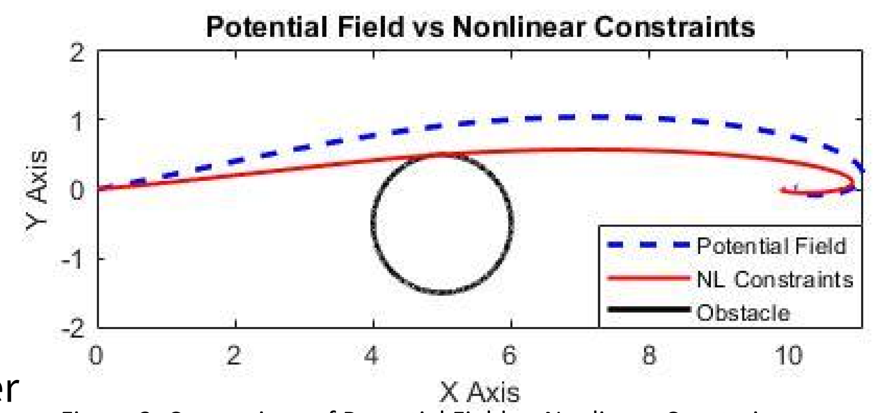

Figure 3: Comparison of Potential Field vs Nonlinear Constraints

## Distributed Model Predictive Control

**Advantages vs Centralised:**
- Reduced computational burden
- Resilient to local failures, inc. communications
- Scalability
- Modularity
- Reconfigurability

**Disadvantages vs Centralised:**
- Suboptimal
- Relies on communication

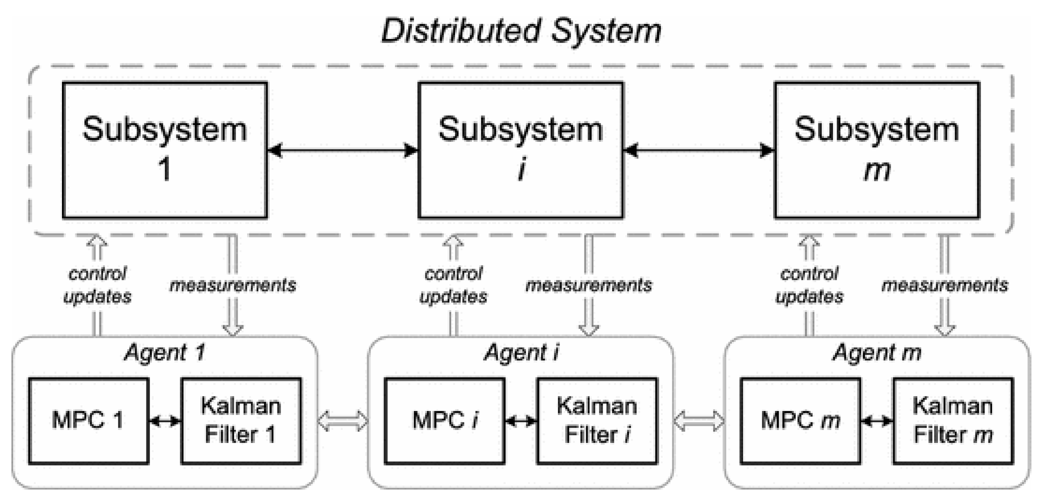

Figure 4: Distributed Predictive Control framework taken from [3]

## Parametric Curves / Trajectory Parameterisation

**Key Part:** Rather than using single waypoints, use a "compressed" smooth representation of the planned trajectory

**Advantages:**
- Reduced computational burden
- Smooth trajectories with competitive performance if appropriately tuned
- Capture a large plan with few variables
- Less bandwidth requirements
- Less information to encrypt/decrypt

**Disadvantages:**
- Can be slightly suboptimal
- Less flexible due to limited options

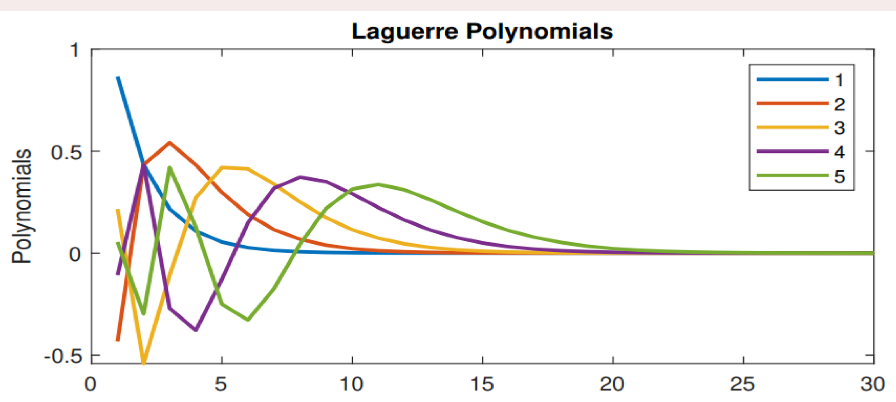

Figure 5: Example of Laguerre Polynomials

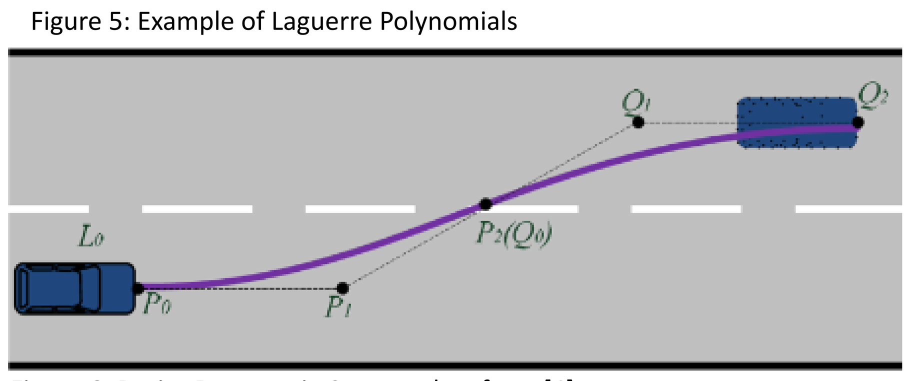
Figure 6: Bezier Parametric Curves taken from [4]

## Legible Control Systems (Player/Observer)

**Key Questions for Player:**
- Can an external observer infer my intentions?
- How can we design our control systems for our actions/plans to be legible by external observers?

**Key Questions for Observer:**
- Can I infer other vehicles' intentions?
- How can this affect my confidence to navigate around or close them?
- Should this have a separate state?

**Key Questions for the Player/Observer Scheme:**
- Can we use this scheme to perform external diagnosis? Eg. Is that vehicle under attack?
- What can we as observers do when we think another vehicle is under attack? Ie. What are the mitigation plans?

**Example application:**
- Overtaking manoeuvre in highway taken from [1]: The vehicle announces the intention by leaning to the left side of the lane before actually executing manoeuvre.

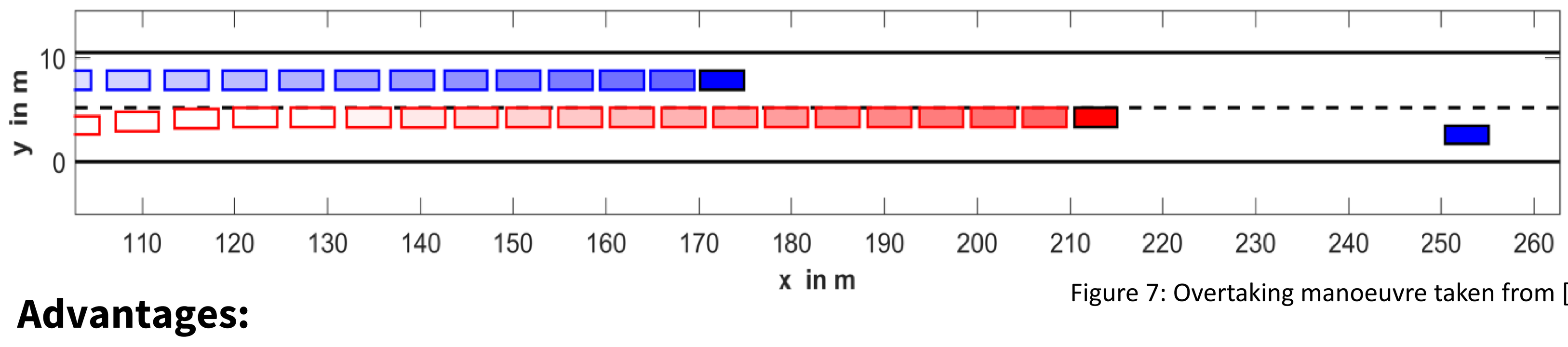

Figure 7: Overtaking manoeuvre taken from [5]

**Advantages:**
- Ability to "broadcast/announce" an autonomous vehicles' intentions.
- Deconfliction of plans when lost or inexistent communication
- External diagnosis of the state of a vehicle for security-related purposes.
- Prevent collateral damage of an attack.

**Disadvantages:**
- Increases the complexity of the control system design.

## Simulation Results

**Case Study:** Large-scale obstacle avoidance/ deconfliction of 50 Multi-rotor UAVs within a cylindrical airspace of 15 meters radius with a height of 10 meters.

**Simulation Assumptions/Specifications:**
- The UAVs have a simplified unity mass-damper model with force/accelerations as inputs, commonly used for path planning.
- Each UAV is targeting a randomly generated waypoint which passes close to the centre of the cylinder and changes approximately every 3 seconds or when the waypoint is reached, and are required to maintain a minimum distance of 1 meter to each other.
- Laguerre-based Distributed MPC: Each UAV has its own control system which takes into account the parameterised paths from all the nearby UAVs.
- There exist constant communication between all UAVs.

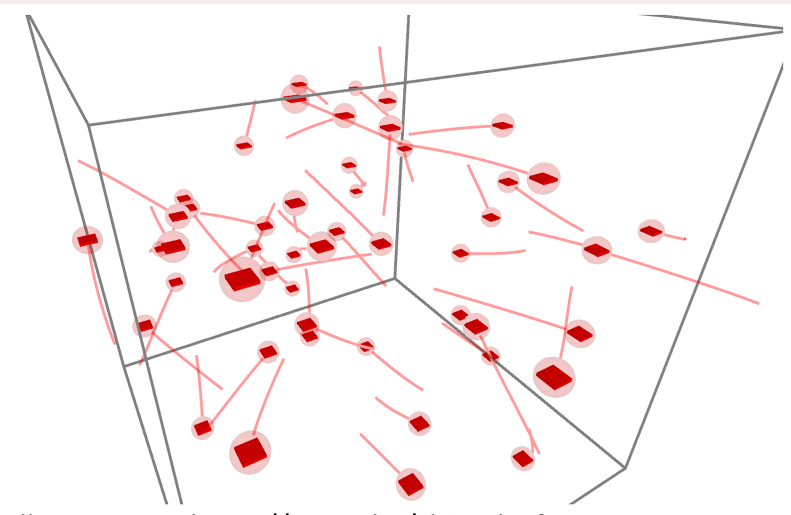
Full Animation: https://youtu.be/LhTsyzlaFfw

Figure 8: Large scale obstacle avoidance animation

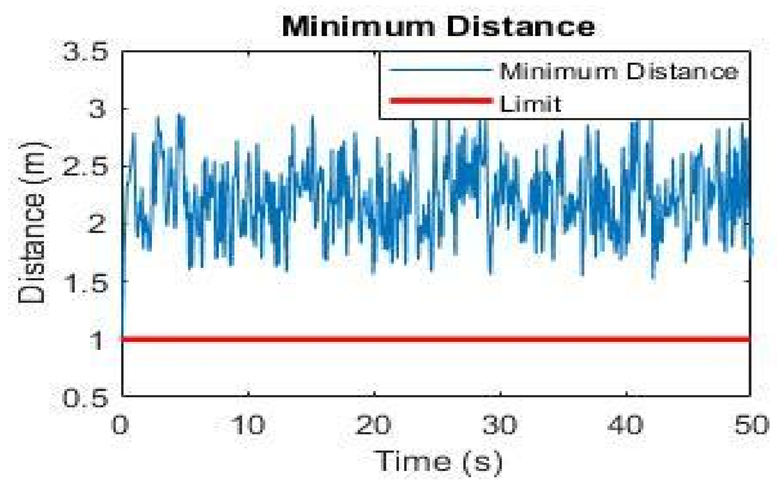

Figure 9: Minimum distance between the UAVs.

## Future Work

**1st Stage:**
- Develop efficient autogenerated algorithms for its implementation.
- Include legibility considerations in the control design for external diagnosis of UAVs state in the presence of various cyber-physical attacks such as communication failures, as well as GPS/Positioning spoofing and jamming.
- Increase the model accuracy to couple with inner UAV dynamics and control systems, as well as to model noise in the system.
- Develop an indoor experimental validation of the proposed approach using the VICON system with at least 5 UAVs.

**2nd Stage:**
- Increase the level of uncertainty from the environment including common GPS positioning errors such as drift, scales or bias, as well as other positioning errors obtained from other sensors such as cameras.
- Develop an outdoor experimental validation of the proposed approach relying only on GPS data.
- Extend the validation to using image processing with sensor fusion for anomaly detection.

## References

[1] S. Jalili, B. Rezaie, Z. Rahmani, "A novel hybrid model predictive control design with application to a quadrotor helicopter", 2018, Optimal Control Applications and Methods

[2] R. Negenborn, B. De Schutter, "Multi-Area Predictive Control for Combined Electricity and Natural Gas Systems", 2015, European Control Conference

[3] S. Roshany-Yamchi, R. Negenborn, A. Cornelio, "Nash-based Distributed MPC for Multi-Rate Systems", 2014, Distributed Model Predictive Control Made Easy. Inteligent Systems, Control and Automation: Science and Engineering, vol. 69, Springer, Dordrecht

[4] L. Claussman, M. Revilloud, D. Gruyer, S. Glaser, "A Review of Motion Planning for Highway Autonomous Driving", 2019, IEEE Transations on Intelligent Transportation Systems

[5] T. Brudigam, D. Wollher, "Legible Model Predictive Control for Autonomous Driving on Highways", 2018, IFAC Conference on Nonlinear Model Predictive Control

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