Formation control of off-road fleet of UGVs: issues, advances and applications
Introduction

**Autonomous vehicle nowadays**
- From dream to actual applications

- Several “well-addressed” issues
  - navigation
  - Perception
  - Control aspects

**Some open issues remaining**
- Human machine interaction
- Sensor and material costs
- Related to All-terrain context
  - Control and positioning accuracy
  - Harsh conditions (terrain geometry, grip conditions)
  - Extending area to be covered

- Extend speed
- Extend number of robots
Introduction

Extend speed of off-road robots
- Face high dynamical effects
  - Inertial effects
  - Low grip conditions
- Important Safety issues
  - Risk of controllability loss
  - Risk of rollover pending on terrain conditions
  - Obstacle avoidance becomes critical

Several robots under cooperation
- Permits to consider limited speed
- High dynamics phenomena neglected
- Several point of views to preserve efficiency

Swarm robotics

Formation Control

Number of robots  scale of robots
Formation control objectives

Several points of view related to cooperation

- Independent control
  - All of robots has its own area
  - Few interaction
  - Separate work

- Robots work together
  - May be associated to achieve a bigger task
  - May be controlled or supervised
  - May achieved complementary works

Coordinated control under some formation

- Preserve repeatability
- Ensure a high level of accuracy
- Preserve its integrity and safety
- Have to be adaptable (variable shape)

Field covering  Unloading (virtual link)  Back home
Overview

Classical motion control of robots

- Classical mobile robot modelling
- Limitations and accuracy requirements

Modeling in off-road conditions

- Extended kinematic model of a fleet of robots
- Observation of bad grip conditions

Control under bad grip conditions

- Lateral dynamic control
  - Extension of a single robot approach
  - Desired set point computation
  - Predictive approach
- Longitudinal dynamic control
  - Reactive approach
  - Relation with other robots
  - Predictive approach and motion anticipation

Extension to target tracking

- Common framework
- Algorithm generalization
Formation control issues in off-road context

Harsh and variable conditions
- Environments and terrain properties
- Robot design and capabilities
- Perception and communication state
- Phenomena to be accounted?

Overview of the control approach
- Modeling of the fleet
- Adaptive layer
- Predictive layer

\[
\delta = \frac{x_{\text{obs}} - f_{\text{obs}}(x_{\text{obs}}, u_{\text{obs}})}{\hat{\beta}^F, \hat{\beta}^R}
\]

Observer law (sliding var.)

Control law

Actual process

Sensor: RTK-GPS

Reference

Leader Data
Modeling of robots formation

*Formalism in the path tracking framework*

- Considers n>1 robots
  - Let us take 2 successive robots Robots \( i \) and \( i+1 \).
- Assumption 1: longitudinal and lateral dynamics are independent
  - Speed variation does not affect lateral performances
  - This is ensured for a single robot by the control law formalism
- Assumption 2: Rolling without sliding conditions

\[
\begin{align*}
\dot{s} &= v \frac{\cos(\tilde{\theta} + \delta_R)}{1 - c(s)y} \\
\dot{y} &= v \sin(\tilde{\theta} + \delta_R) \\
\dot{\tilde{\theta}} &= v \left[ \cos(\delta_R) \frac{\tan(\delta_F) - \tan(\delta_R)}{L} - c(s) \frac{\cos(\tilde{\theta} + \delta_R)}{1 - c(s)y} \right]
\end{align*}
\]
Classical path tracking control

Satisfactory when assumptions are valid
Classical path tracking control

Satisfactory when assumptions are valid

Unsuitable when running on natural ground [depends on speed!]
Theoretical influence on formation control

Motion at 3 m/s

- Global path tracking with a stopping vehicle and 5 robots
  - Relative positioning and servoing
  - Longitudinal distance of 3m
  - Lateral: -2, +2, 0, 0.

- Simulation using ideal conditions

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- Ideal localization perception
- Ideal communications
- Ideal grip conditions
- Ideal actuators
Theoretical influence on formation control

Motion at 3 m/s

- Global path tracking with a stopping vehicle and 5 robots
  - Relative positioning and servoing
  - Longitudinal distance of 3m
  - Lateral: -2, +2, 0, 0.

- Simulation using ideal grip conditions, actuators, sensors and communication

- Simulation using bad grip conditions, delayed sensor and perception
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Modeling of robots formation

Extended model

- Considers \( n > 1 \) robots
  - Let us take 2 successive robots \( i \) and \( i+1 \).

- Assumption 1: longitudinal and lateral dynamics are independent
  - Speed variation does not affect lateral performances
    - This is ensured for a single robot by the control law formalism

- Assumption 2: Rolling without sliding conditions

\[
\begin{align*}
\dot{s} &= V_r \frac{\cos(\delta + \delta_R - \beta_R)}{1 - c(s)} y \\
\dot{y} &= V_r \sin(\delta + \delta_R - \beta_R) \\
\dot{\theta} &= V_r \left[ \cos(\delta_R - \beta_R) \lambda_1 - \lambda_2 \right]
\end{align*}
\]
Sideslip angle observation (virtual measure)

**General scheme of observation**

- A second loop is designed
  - Convergence of model output to measure
  - Using sideslip angles computation
- Assumptions for reconstruction
  - Convergence of model output to measure
  - Using sideslip angles computation

**Observer design**

Measured state: \( \dot{X} = \begin{bmatrix} \dot{y} \\ \dot{\theta} \end{bmatrix} \)

Derivative:

\[
\dot{X} = \begin{bmatrix} \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{v \sin (\hat{\theta} + \delta_R + \beta_R)}{\cos(\delta_R + \beta_R)} - \frac{v \sin (\hat{\theta} + \delta_R + \beta_R)}{L} \\
\frac{v \cos(\delta_R + \beta_R) \left( \tan \delta_F + \beta_F - \tan \delta_R + \beta_R \right) - c(s) v \cos(\hat{\theta} + \delta_R + \beta_R)}{1 - c(s) y} \end{bmatrix}
\]
Modeling of robots formation

Motion model stay unchanged

- For the \( i \)th robot
  - Controls: velocity, steering angles(s)
  - State: Cirv. Absc. lateral + angular deviations

- Kinematic model is let unchanged

\[
\dot{X} = \begin{bmatrix}
\dot{s} \\
\dot{y} \\
\dot{\theta}
\end{bmatrix} = \begin{bmatrix}
v \cos(\hat{\theta}+\delta_k+\beta_R) \\
v \cos(\delta_k+\beta_R) - \tan \delta_k \tan \beta_R - c(s) v \cos(\hat{\theta}+\delta_k+\beta_R) \\
v \cos(\delta_k+\beta_R) - \tan \delta_k \tan \beta_R - c(s) v \cos(\hat{\theta}+\delta_k+\beta_R)
\end{bmatrix}
\]

- In counterpart the set point changes to describe relative positions
  - Lateral deviation may defined different from zero and variable
  - The velocity may be computed to ensure longitudinal distances

- Control objectives
  - Lateral: 
    \[ y_{i+1} \rightarrow y^d(y_i) \]
  - Longitudinal: servo the curvilinear distance 
    \[ s_i - s_{i+1} \rightarrow d_i \]
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Lateral dynamic control

The same principle as for a single robot may be used

- Control objective \( y_i \rightarrow y_i^d \)
  - Whatever the speed
  - Whatever the potential rear steering angle
  - Knowing the grip conditions

- Using exact linearization
  - Variable transformation
    \[
    [s_i, y_i, \theta_i] \rightarrow [a_{1i}, a_{2i}, a_{3i}] = [s_i, y_i, (1 - c(s_i) y_i) \tan(\theta_i + \beta_i^R)]
    \]
    \[
    [\bar{u}_i, \delta_i] \rightarrow [m_{1i}, m_{2i}] = \left[ \frac{\bar{v}_i \cos(\theta + \beta_i^R)}{1 - c(s_i) y_i}, \frac{d a_{3i}}{dt} \right]
    \]
  - Chained system form \( \rightarrow \) derivative w.r.t curvilinear abscissa
    \[
    \begin{align*}
    \dot{a}_{1i} &= \frac{da_{1i}}{dt} = m_{1i} \\
    \dot{a}_{2i} &= \frac{da_{2i}}{dt} = a_{3i} m_{1i} \\
    \dot{a}_{3i} &= \frac{da_{3i}}{dt} = m_{2i}
    \end{align*}
    \]
  - Virtual control law
    \[
    m_{3i} = -K_d(a_{3i} - y_i^d) - K_p(a_{2i} - y_i^d) + y_i^{nd} \quad (K_d, K_p > 0)
    \]
    \[
    \dot{\epsilon}_i^y + K_d \epsilon_i^y + K_p \epsilon_i = 0 \quad \text{with} \quad \epsilon_i = a_{2i} - y_i^d
    \]
Lateral dynamic control

Computation for a given robot $i$

- Control design

  Expression

  $$m_{3i} = -K_d(a_{3i} - y_{i}^d) - K_p(a_{2i} - y_{i}^d) + y_{i}^{ud} \quad (K_d, K_p > 0)$$

  Reverse transformation

  $$[s_i, y_i, \dot{\theta}_i] \rightarrow [a_{1i}, a_{2i}, a_{3i}] = [s_i, y_i, (1 - c(s_i)y_i)\tan(\dot{\theta}_i + \beta_i^R)]$$
  $$[v_i, \delta_i] \rightarrow [m_{1i}, m_{2i}] = \left[ \frac{v_i}{1 - c(s_i)y_i} \frac{\dot{\theta}_i}{\beta_i^R} \right]$$

  Steering angle control law

  $$\delta_i = \arctan\left\{ \tan(\beta_i^R) + \frac{l}{\cos(\beta_i^R)} \left( \frac{c(s_i)\cos(\dot{\theta}_i^R)}{\alpha_i} + \ldots \right. \right.$$
  $$\left. \left. \ldots \frac{A_i \cos(\delta_i)}{v_i \alpha_i^2} \left(\dot{\theta}_i^R\right) \right\} + \beta_i^F,$$

  $$\begin{align*}
  \tilde{\theta}_i &= \dot{\theta} + \beta_i^R \\
  \alpha_i &= 1 - c(s_i)y_i \\
  A_i &= -K_p c_i^y - K_d \alpha_i \eta + c(s_i)\alpha_i \eta \tan(\tilde{\theta}_i^2) \\
  \eta &= \left( \frac{\tan(\tilde{\theta}_i^2) - \frac{y_i^d}{v_i \cos(\tilde{\theta}_i^2)}}{v_i \cos(\tilde{\theta}_i^2)} \right) \\
  \psi &= 1 + \tan^2(\tilde{\theta}_i^2) - \frac{y_i^d \tan(\tilde{\theta}_i^2)}{v_i \cos(\tilde{\theta}_i^2)}
  \end{align*}$$

- Based on the same assumption and methodology than for a single robot with set points

  - Settling distance is theoretically independent from velocity
  - Convergence to a desired lateral distance
  - Actuator settling time and delays are neglected

How the relationship with others is ensured ??????
Lateral dynamic control

Lateral desired set point account for other robot

- Several points of view may be investigated
  - Defined with respect to common reference path
  - Defined with respect to previous robot deviation

Example of a mixed definition

\[ y_i^d = \bar{d}_i^y + \sigma [y_{i-1} - \bar{d}_{i-1}^y] \]

\sigma = 0
Robots move independently

\sigma = 1
Robots move w.r to previous one

Perfect multi robot field covering
Platooning
Coming back home

Hazardous robot field covering
Virtual link
Independent tracking

Depends on previous behaviour
Lateral dynamic control

**Control strategy**

- Path tracking based approach using a common reference
- A non null desired distance is defined
- Lateral control law is slightly modified, but methodology is preserved
Lateral dynamic control

**Control strategy**

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**Extensions**

- Predictive control may be used if future trajectory is available (see next part)

Ensemble diagram:

- Reactive term $x_i$
- Separation
- Ref path
- Future curvature
- Predictive minimization
- Predictive control

- Introduction of a composite error pending on other robots deviation
  - Let us define several errors with other robots
  - Define a global error as a linear combination of elementary errors
  - Key issue: defined a rule for varying coefficient
Lateral dynamic control

Actual results

- B/ Prediction addon interest

- speed: 2m/s

Communication WIFI

1. Constant desired deviation at 2m, and -3m
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Longitudinal dynamic control

Velocity control

- Velocity servoing objective: \( s_i - s_{i+1} \to d_i \)
  - Ensure a curvilinear distance
  - Whatever the lateral position
  - Whatever the grip condition

- With respect to the previous robot

  Error definition
  \[
  e_{i+1} = s_i - s_{i+1} - d_i
  \]

  Desired behavior for the convergence of the defined error to zero
  \[
  \dot{e}_{i+1} = K_{i+1} e_{i+1}
  \]

  Time derivative (or derivative w.r. to curvilinear abscissa)
  \[
  \dot{e}_{i+1} = v_i \frac{\cos(\bar{\theta}_{2i})}{1 - c(s_i)y_i} - v_{i+1} \frac{\cos(\bar{\theta}_{2(i+1)})}{1 - c(s_{i+1})y_{i+1}} - d_i
  \]

  Control law expression for velocity may be deduced (w.r to robot i):
  \[
  v_{i+1} = \frac{1 - c(s_{i+1})y_{i+1}}{\cos(\bar{\theta}_{2(i+1)})} \left[ v_i \frac{\cos(\bar{\theta}_{2i})}{1 - c(s_i)y_i} - K_{i+1} e_{i+1} \right]
  \]
Longitudinal dynamic control

Velocity control

- Other distance to be defined
  - If control is refereed only with respect to previous robot
    - Errors may be propagated over the formation
  - If previous robots stop, the follower will stop too
    - If the last one stops ???

Control with respect to robot $i$

- Same methodology, defining the distance with first robot considered as a leader
  - Only index and desired distance change
    - Error
      - $e_{i+1}^i = s_i - s_{i+1} - d_i$
      - $e_{i+1}^1 = s_1 - s_{i+1} - \sum d_m$
      - $v_{i+1} = \frac{1 - c(s_{i+1})y_{i+1}}{\cos(\tilde{\theta}_{2(i+1)})} \left[ v_A \frac{\cos(\tilde{\theta}_{21})}{1 - c(s_1)y_1} - K_{i+1}^l e_{i+1}^1 \right]$
  - Control only with respect to the leader
    - No error propagation (a unique reference)
    - If a previous robot (except the leader) stops
      - If the last robot stops?
Hybrid distance regulation

- The velocity control may regulate several distance between robots

\[
u_{i}^{k} = \frac{1 - c(s_{i})y_{i}}{\cos(\theta_{i} + \beta_{R}^{i})} \left( \frac{\cos(\theta_{k} + \beta_{k}^{R})}{1 - c(s_{n})y_{n}} + k_{k}^{i} e_{i}^{k} \right)
\]

- Collection of n-1 control law (or n-1 relative distance)

\[
e_{i}^{k} = s_{i} - s_{k} - \sum_{j=k}^{i} d_{j}
\]

- Selection/weighting process

- Different functions: Safety/formation control/insertion...
Longitudinal dynamic control

Results without prediction

- Parameters
  - Leader: 2m/s
  - Desired dist.: constant = 9m
  - Lateral dev.: -2m
Predictive longitudinal dynamic control

Control law extension

- Predictive control 2: Feedforward and prediction
  
  **Step 1**: Feedforward - Future distance may be computed
  
  \[ e_{i+1}^i = s_i - s_{i+1} - d_i \]

  \[ e_{i+1}^i (t + H) = s_i (t + H) - s_{i+1} (t + H) - d_i \]

  **Step 2**: Future desired velocity is derived

  \[ v_{ik}^k = \frac{1 - c(s_i) y_i}{\cos(\tilde{\theta}_i + \beta_R^k)} \left( \frac{\cos(\tilde{\theta}_k + \beta_R^k)}{1 - c(s_n) y_n} \right) + k_i^k e_i^k \]

  **Step 3**: Model predictive control is applied using future set point for velocity

Error and curvature are anticipated
Predictive longitudinal dynamic control

Results with 2 prediction levels

- Parameters
  - Leader: 2m/s
  - Desired distance: constant = 9m
  - Lateral set point: 3m
Motion control – 2 – Formation control results

Fixed configuration, robustness w.r to terrain geometry

Leader at 2m/s
Desired Long: 9m
Desired Lat: 1m
Inclination of 15°
Accuracy <15cm
Motion control – 2 – Formation control results

Variable configuration and predictive control interest

![Graphs showing interdistance and lateral deviation over curvilinear abscissa](image)
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Formation control with a free leader

Target may be manually controlled or directly a moving object

- Trajectory is not necessarily achievable
- Variations may be impossible to follow

The same control strategy may be used

- Similar model may be used
- Reference trajectory is viewed as successive target positions

\[
\begin{align*}
\Gamma & \quad \text{Moving target} \\
O & \quad y \\
& \quad \delta \\
& \quad \tilde{\theta} \\
& \quad s \\
& \quad v \\
& \quad d
\end{align*}
\]
Formation control with a free leader

Results with an achievable trajectory target

- target = remotely controlled robot
- Using RTK-GPS sensors
- All-terrain conditions
**Formation control with a free leader**

*Results with an achievable trajectory target*

- Trajectory followed

- Tracking errors

![](image-url)
Formation control with a free leader

Actual results

- Without predefined reference Traj
  - speed: 2 m/s
  - WIFI communication

Variable lateral deviation 0 → 2m
Constant desired distance 12m
3 vehicles (2 robots considered)
High accuracy despite variations (slope, speed, ...)

![Diagram showing formation control results](image-url)
Formation control with a human target

Pedestrian following with a desired distance

- Using inertial navigation

- Using another type of robot
  
  Car like $(v, \delta)$

  Skid steering $(v, \dot{\theta})$
Formation control with a human target

Pedestrian following with a desired distance

- Using inertial navigation
Robot cooperation in the framework of formation

Viewed as an extension of path tracking

- Longitudinal and lateral dynamics have discoupled
  - Using exact linearization of steering angle control (see course 1)
  - This may be true whatever the control strategy

- Lateral control
  - Steering angle or yaw rate, stay unchanged
  - But the set point is modified (relative lateral position)

- Longitudinal control (velocity)
  - Using a defined curvilinear distance
  - Elementary control law with respect to one robot
  - Extension and weighting of n-1 elementary control laws

- Predictive principles may be added to improve robustness with respect to settling times
  - 1. Feedforward control in order to anticipate for errors
  - 2. The future set point may be derived
  - 3. Model predictive control is then applied

In off-road conditions, it uses extended kinematic model...
Regarding robots an terrain interaction

- Grip conditions are addressed one by one
- Skidding estimation to be shown in next lecture

Regarding fleet management

- Obstacle avoidance and management
  - Perception problem w.r. to Numeric Terrain Model
  - Avoidance may be addressed using non null lateral set point
- Robot addition and removal
  - On-line modifications of control laws number
  - On-line modification of weighting functions

Regarding robots safety

- Safety distance must be ensured
  - Not necessarily compatible with desired set point (pending on speed)
  - Ability to compute safety distance?
- Control must account for localization accuracy and availability

Supervision process must manage desired distances and control laws