Researchers
PhD Students
Support
Services


Kinematics and Robot Design
Mobile Robotics
Perception and Manipulation
Automatic Control

Peception and Manipulation Laboratory
Kinematics and Robot Design Laboratory
Mobile Robotics Laboratory
Barcelona Robot Laboratory
Fuel Cell Control Laboratory
Water-cycle Control Systems Laboratory
Human pose estimation using CV and CNNs (CVPR, ICCV, IJCV)
In the Institute we think that it is good to involve all our members in informative activities that attempt to bring science to all audiences. For this reason, our staff participates frequently in many events such as seminars, workshops, talks, exhibitions and competitions.

OUTREACH
>
Numerous guided visits to IRI
MIPRCV Industry Day, Barcelona 2011, Barcelona
International Conference on Computer Vision ICCV 2011 and 2012 edition of CEABOT, Sevilla and Vigo
Campus Party 2011, València
Smart City Expo World Congress 2012, Barcelona
Saló del Còmic 2012, Barcelona
2011 and 2012 edition of European Robotics Week
2011 and 2012 edition of Setmana de la Ciència
Exhibition “I/O/I Els sentits de les màquines”, BCN, 2011

Research projects related to sewer network.

CORAL

The CORAL improvements have been satisfactory tested and improvement and multi-objective prioritisation.

Coral upgrade RCT1 2012

Research center created in 2006 and cofounded by CSIC, UPC

The collaborative project between IRI and CET aqua, a research center of RTI, will involve the development of new advanced controllers capable to improve the efficiency of fuel cells.

Advanced controllers and observers development for fuel cell and open cathode fuel cells

ACRES

The key aim of this project is the development of advanced renewable energy technologies research.

ACOFC

The activities proposed in this project strive for providing solutions to problems arisen from the current energy system, based mainly on hydrocarbons and has a firm commitment to encourage the use of renewable energy.

Advanced controllers for new hybrid electrical generation systems

MACPERCON

The aim of the project is to improve the PEMFC systems performance and of efficiency and lifetime improvement of PEM fuel cells based generation systems. Special efforts will be focused on obtaining innovative results in the area of PEM fuel cells control oriented models, dynamic estimation of states and new operational variables and nonlinear control based on Higher Order Sliding Modes. Considerable work with new techniques to improve the efficiency in water systems, including energy management strategies.

Design and implementation of control systems for PEM fuel cells and their integration into distributed electrical power generation systems

DISCPICO

The results will contribute to the definition of an integrated hydrogen based energy system, which has been seen as a possible scenario for future energy supply in Europe. The particular strategy corresponds with the unfalsified control, which is based on the idea of commutation of controllers depending on a desired system performance. Additionally, it is expected to complement the proposed control designs with other modern control strategies such as model predictive control (MPC).

Enhanced management topologies based on unfalsified control for PEM fuel cells performance improvement

MACPERCON explores the way of analysing, designing and performing. Furthermore, it is expected to complement the proposed control designs with other modern control strategies such as model predictive control (MPC).
Current projects, Perception and Manipulation + Kinematics Groups

IMAGINE: Robots Understanding Their Actions by Imagining Their Effects
H2020-ICT-2016-1-731761

SOCRATES: SOcial Cognitive Robotics in The European Society
H2020-MSCA-ITN-721619

I-DRESS: Assistive interactive robotic system for support in dressing
PCIN-2015-147

RobInstruct: Instructing robots using natural communication skills
TIN2014-58178-R

RobCab: Control strategies for cable-driven robot for low-gravity simulation
DPI2014-57220-C2-2-P

Cloth manipulation learning from demonstrations

ERC Advanced Grant  (ERC-2016-ADG-741930)
Current projects, Automatic Control Group

INN-BALANCE: INNovative Cost Improvements for BALANCE of Plant Components of Automotive PEMFC Systems
H2020-JTI-FCH-2016-1-735969

INCITE: Innovative controls for renewable sources integration into smart energy systems
H2020-MSCA-ITN-675318

EFFIDRAIN: Efficient Integrated Real-time Control in Urban Drainage and Wastewater Treatment Plants for Environmental Protection
LIFE14 ENV/ES/000860

GRACeFUL: Global systems Rapid Assessment tools through Constraint FUnctional Languages
H2020-FETPROACT-2014-640954

DEOCS: Monitorización, diagnostico y control tolerante a fallos de sistemas ciberfísicos con métodos basados en datos
DPI2016-76493-C3-3-R

MICAPEM: Parameter estimation, diagnosis and control for the improvement of efficiency and durability of PEM fuel cells
DPI2015- 69286-C3-2-R
Current projects, Mobile Robotics Group

AEROARMS: Aerial Robotics System integrating multiple ARMS and advanced manipulation capabilities for inspection and maintenance
H2020-ICT-2014-1-644271

ECHORD++: European Clearing House for Open Robotics Development Plus Plus
FP7-ICT-2011-9-601116

Cargo-ANTS: Cargo handling by Automated Next generation Transportation Systems for ports and terminals
FP7-SST-2013-RTD-1-605598

LOGIMATIC: Tight integration of EGNSS and on-board sensors for port vehicle automation
H2020-Galileo-2015-1-687534

ColRobTransp: Colaboración robots-humanos para el transporte de productos en zonas urbanas
DPI2016-78957-R
Visual Guidance of Unmanned Aerial Manipulators

Juan Andrade Cetto

Based on the work of: Angel Santamaria Navarro

with contributions from: L. Bascetta, V. Cacace, Y.R. Esteves, P. Grosch, V. Kumar, V. Lippiello, A. Loianno, D. Lunni, P. Rocco, R. Rossi, and J. Solà, and M.A. Trujillo, A. Viguria
Aerial Robots

Unmanned Aerial Manipulators (UAM)

Goal: Autonomous operation

Challenges
Tasks
- Navigation
- Manipulation
...

Control
- Joint positions
- Joint velocities
...

Perception
- State estimation
- Target detection
...
Outline

- Robot state estimation
- Visual servo control
- Task control
- Conclusions
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**Robot state estimation**

**Target:** UAM platforms
- Light-weight and low-cost sensors
- Limited CPU

**Goal:**
- Where am I?

**Robot state**
- position
- velocity
- acceleration

**State estimation methods**
- Sliding window
- Full trajectory

**Accuracy**
- Simple algorithms

**Complexity/Resources**
- Current estimate
- Sliding window

**Target:**
- Setup
- Design
- Experiments
- Remarks
System setup

Visual-inertial

- Light weight, low cost
- Account for system dynamics
- Register gravity vector

IMU

- Accelerometers
- Gyroscopes

Smart camera (SC)

- 2D raw optical flow
- Height (sonar)
- 2D linear velocities

IR Ranger

- Height

Setting A
- IMU
- SC: 2D linear vel.
- SC: Sonar range

Setting B
- IMU
- SC: 2D opt. flow
- IR range
Simplicity vs. Performance: What’s the trade-off?

- **Benchmark Kalman filter variants**
  - (B1) Extended (EKF) vs. Error-State (ESKF)
  - (B2) ESKF: Orientation error definition (global, local)
  - (B3) (B4) Integration approx. (taylor, quaternion)
• Extended Kalman Filter (EKF): Direct estimation of $\mathbf{x}_t$

$$\mathbf{x}_t = \begin{bmatrix} p_t & v_t & q_t & a_{bt} & \omega_{bt} \end{bmatrix}^\top$$

• Error State Kalman Filter (ESKF):

$$\mathbf{x}_t = \mathbf{x} \oplus \delta \mathbf{x} \quad \mathbf{x} = \begin{bmatrix} p & v & q & a_b & \omega_b \end{bmatrix}^\top$$

$$\mathbf{x} = \begin{bmatrix} p & v & q & a_b & \omega_b \end{bmatrix}^\top$$

$$\mathbf{x} = \begin{bmatrix} p & v & q & a_b & \omega_b \end{bmatrix}^\top$$

$$\delta \mathbf{x} = \begin{bmatrix} \delta p & \delta v & \delta \theta & \delta a_b & \delta \omega_b \end{bmatrix}^\top$$

(B2) ESKF: Orientation error definition

- Global error (GE): $q_t = \delta q \otimes q$
- Local error (LE): $q_t = q \otimes \delta q$
Robot state estimation

Continuous system kinematics

\[ \dot{x} = f(x, u) \] (nonlinear)

Discrete system kinematics

\[ x_k \approx F x_{k-1} + Bu \Delta t \]

(B3) Taylor series with different truncation grade

\[ F = e^{A \Delta t} \rightarrow F_N \approx I + A \Delta t + \frac{1}{2} A^2 \Delta t^2 + \ldots + \frac{1}{N} A^N \Delta t^N \]

(B4) Quaternion integration

Q0F: \[ q_k \approx q_{k-1} \otimes q(\omega_{k-1} \Delta t) \]

Q0B: \[ q_k \approx q_{k-1} \otimes q(\omega_k \Delta t) \]

Q1: \[ q_k \approx q_{k-1} \otimes \left( q(\omega \Delta t) + \frac{\Delta t^2}{24} \left[ \begin{array}{c} 0 \\ \omega_{k-1} \times \omega_k \end{array} \right] \right) \]
Simulations

Setting A

- IMU
- SC: 2D linear vel.
- SC: Sonar range

X, Y and Yaw
non observable: Odometer

Acc. Biases
observability depending on platform tilt

Ang. Vel. Bias
(Yaw) observable after long period!
Simulations

Setting B

- IMU
- SC: 2D opt. flow
- IR range

Estimation error after 10min flights of 500m in straight line

<table>
<thead>
<tr>
<th>Error Component</th>
<th>Filter Variant</th>
<th>EKF $F_1$ Q0F LE</th>
<th>EKF $F_1$ Q0B LE</th>
<th>EKF $F_1$ Q1 LE</th>
<th>EKF $F_2$ Q1 LE</th>
<th>EKF $F_3$ Q1 LE</th>
<th>ESKF $F_1$ Q0F GE</th>
<th>ESKF $F_1$ Q0B GE</th>
<th>ESKF $F_1$ Q1 GE</th>
<th>ESKF $F_2$ Q1 GE</th>
<th>ESKF $F_3$ Q1 GE</th>
<th>ESKF $F_1$ Q0F LE</th>
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<tr>
<td>y [m]</td>
<td>11.13</td>
<td>11.07</td>
<td>10.85</td>
<td>10.81</td>
<td>11.00</td>
<td>10.82</td>
<td>10.55</td>
<td>10.58</td>
<td>10.58</td>
<td>10.58</td>
<td>10.91</td>
<td></td>
</tr>
<tr>
<td>z [mm]</td>
<td>7</td>
<td>6</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>7</td>
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<td></td>
</tr>
</tbody>
</table>

Root Mean Squared Error (RMSE) over 20 experiments
Real robot experiments

Setting A

- Accelerometers
- Gyroscopes
- 2D linear velocities
- Ranger (sonar)

Setting B

- Accelerometers
- Gyroscopes
- 2D raw optical flow
- Ranger (IR)

Control loop with a nonlinear tracking controller on $SE(3)$
Setting A

Indoor

Outdoor

0.5m error after 2min flight (avg.)
Setting B

Research stay at UPenn

Error analysis

2 traj. with 25 runs each.

10 min flight (full battery discharge)

RMSE (m) [0.47 0.67 0.035]
State estimation remarks

• **Light-weight, low-cost** sensors and **low-complexity** algorithms

• **Benchmark** of Kalman filter variants:
  ‣ All filters perform equally (@100Hz)
  ‣ Acceptable errors for autonomous navigation


Outline

- Robot state estimation
- Visual servo control
- Task control
- Conclusions
**Objective:** drive the robot using visual information

**Reduce** the error between current and desired points of view

\[ e(t) = s(t) - s^d \]

\[ e = -\lambda \dot{e} = -\lambda J^c \dot{\vartheta} \]

\[ 6\text{DoF camera vel.} \quad c \vartheta = -\lambda J^e e \]

- Position-based (PBVS)
- Image-based VS (IBVS)
- Hybrid VS (HVS)
**Schemes**

**PBVS:** Position-based visual servo

\[ \mathbf{s} = \{ \mathbf{u}, \nu \} \quad \mathbf{s}^d = \{ \mathbf{u}^d, \nu^d \} \]

**IBVS:** Image-based visual servo

**HVS:** Hybrid visual servo

PBVS + IBVS
**IBVS**: Image-based visual servo

- Image Jacobian depends on focal length

\[ ^c \theta = -\lambda J^+ e \]

\[ J = [J_1^\top \ldots J_n^\top]^\top \quad (n \text{ features}) \]

\[ J_j = \begin{bmatrix} -\frac{1}{z} & 0 & \frac{u}{z} & uv & -(1 + u^2) & \nu \\ 0 & -\frac{1}{z} & \frac{v}{z} & (1 + v^2) & -uv & -u \end{bmatrix} \]

**UIBVS**: Uncalibrated image-based visual servo
Uncalibrated image-based visual servo (UIBVS)

- Drawing inspiration on EPnP and UPnP algorithms

Set 4 control points (CP) as a basis of the target frame

Target pose = 3D coordinates of CP in camera frame
Visual Servo Principle Schemes **UIBV** Simulations Remarks

- Each target features as a function of CP
- Perspective projection equations

\[ M \mathbf{x} = 0 \]

2D-3D correspondences

12 unknowns \[ \mathbf{x} = [x_1, y_1, z_1/\alpha, \ldots, x_4, y_4, z_4/\alpha]^T \]

SVD

\[ \mathbf{x} = \beta \mathbf{\mu} \]

\[ \mathbf{\mu} \]: Eigenvector of null eigenvalue of \( M^T M \)

Solve for \( \alpha \) and \( \beta \)

Distances between CP must be preserved (+6 constraints)

![Diagram of target and camera with coordinates and vectors]
• Uncalibrated image Jacobian

\[
J_j = \begin{bmatrix}
\frac{-1}{\beta \mu_z} & 0 & \frac{\mu_x}{\alpha \beta \mu_z^2} & \frac{\mu_x \mu_y}{\alpha \mu^2} & -\frac{\mu_x^2 - \alpha^2 \mu_z^2}{\alpha \mu_z^2} & \frac{\mu_y}{\mu_z} \\
0 & \frac{-1}{\beta \mu_z} & \frac{\mu_y}{\alpha \beta \mu_z^2} & \frac{\mu_y^2 + \alpha^2 \mu_z^2}{\alpha \mu_z^2} & -\frac{\mu_x \mu_y}{\alpha \mu_z^2} & -\frac{\mu_x}{\mu_z}
\end{bmatrix}
\]

\[
J = [J_1^T ... J_4^T]^T
\]

6DoF camera vel. 

\[
c \dot{\theta} = -\lambda J^+ e
\]
Simulations

(real experiments results are shown in Task Control section)

**Camera velocities during a servo task**
subject to **white noise** of 1 mm in the focal length

**Focal length variations** become undesired camera velocity references for PBVS and IBVS
Initialization error in camera focal length

Noise-free

With a wrong initialization 20% PBVS and IBVS are unable to reach the desired configuration
Visual servo remarks

- **New uncalibrated image-based visual servo** method (UIBVS)
  - Target features parameterized with CP coordinates
  - Method to recover CP 3D coordinates and focal length
  - New calibration-free image Jacobian
  - Robustness w.r.t. focal length noise and wrong initialization


Outline

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Kinematics

We need the **robot Jacobian** to map velocities from camera to joint frames.

\[
\xi = \begin{bmatrix} v^T & \omega^T & \dot{\gamma}^T \end{bmatrix}^T
\]

Cam. vel. \( \dot{v} \) = \( J_R \xi \)

Robot DoFs

Bone breaker 1:20 (**FADA-CATEC**)

Kinton 1:10 (**IRI**)

Cam
• Platform under actuation: **Remove uncontrollable DoFs** \( \mathcal{W} \)

\[
\dot{\vartheta}_C = J_R \xi
\]

Uncontrollable (gyros read.)

\[
\dot{\vartheta}_C = J_R \dot{\rho} + \overline{J_R} \mathcal{W}
\]

Weighted pseudo-inverse to **distribute motion**

e.g.

• Platform: large displacements
• Arm: precise movements
UAMs are usually redundant (>6DoF)

Tasks
- Navigation
- Visual servo

We can define a set of different tasks and set priorities according to mission phases

Task combination methods
- Hierarchical control laws (x2)
- Optimization-based approach
**Tasks**

- **Collision avoidance** (obstacles or self-collisions)

\[
\sigma_0 = r_0 - \|d_0\|
\]

- **Visual Servo**
  - Global end effector tracking: **PBVS** using global coordinates
  - Local end effector tracking: **IBVS** or **UIBVS**
  - Keeping target in camera FoV: **HVS** \( \sigma_f = e_f^T e_f \)

- **Arm CoG alignment** with platform gravitational vector

\[
\sigma_g = d_{xy}^T d_{xy}
\]
• Reach a **desired arm configuration**

\[ \sigma_l = (\gamma - \gamma^d)^\top \Lambda_l (\gamma - \gamma^d) \]

current \( \gamma \)  
desired \( \gamma^d \)

• Maximize manipulability index

\[ \sigma_m = \frac{1}{\prod_{i=1}^{r} \mu_i} \]

• Minimize velocity of specific joints
• Limit platform accelerations
• Reduce forces on platform horizontal plane
Hierarchical task control (HTPC)

- Assign priorities with the null space projection technique
- Dynamic change of task priorities

Classical HTPC

Collaboration with FADA-CATEC and UNINA

Exact tracking of the primary task while minimizing secondary task error

Null space projector

\[
\dot{\rho} = J_0^+ \Lambda_0 \tilde{\sigma}_0 + (J_1 N_0)^+ \Lambda_1 \tilde{\sigma}_1 - J_{0|1} \varpi
\]

Can lose rank (algorithmic singularities) + Requires orthogonal or independent tasks

HTPC decoupling algorithmic singularities

Tracking of components that do not conflict with the primary task

\[
\dot{\rho} = J_0^+ \Lambda_0 \tilde{\sigma}_0 + N_0 J_1^+ \Lambda_1 \tilde{\sigma}_1 - J_{0|1} \varpi
\]
Classical HTPC

Grasping

Tasks
- HVS
- Arm CoG alignment
- Desired arm cfg.

- e.e. position error ($\sigma_p$)
- e.e. orientation error ($\sigma_\phi$)
- Camera FoV error ($\sigma_f$)
HTPC decoupling algorithmic singularities

Tasks: UIBVS + arm CoG alignment + desired arm cfg.
Remarks on task control

• Two configurations: onboard camera and camera at the end effector

• Task and constraints designed for UAMs

• New Task control architectures for UAMs


Thank you!

Code + multimedia: http://angelsantamaria.eu

Visual Guidance of Unmanned Aerial Manipulators
Àngel Santamaria Navarro and Juan Andrade Cetto