RFIA 2014

Reconnaissance des Formes et Perception
Intelligence Artificielle

Universidad de Zaragoza

Atelier - Perception pour le véhicule intelligent (P. Vasseur)

Visual Servoing and Exploration for Mobile Robots

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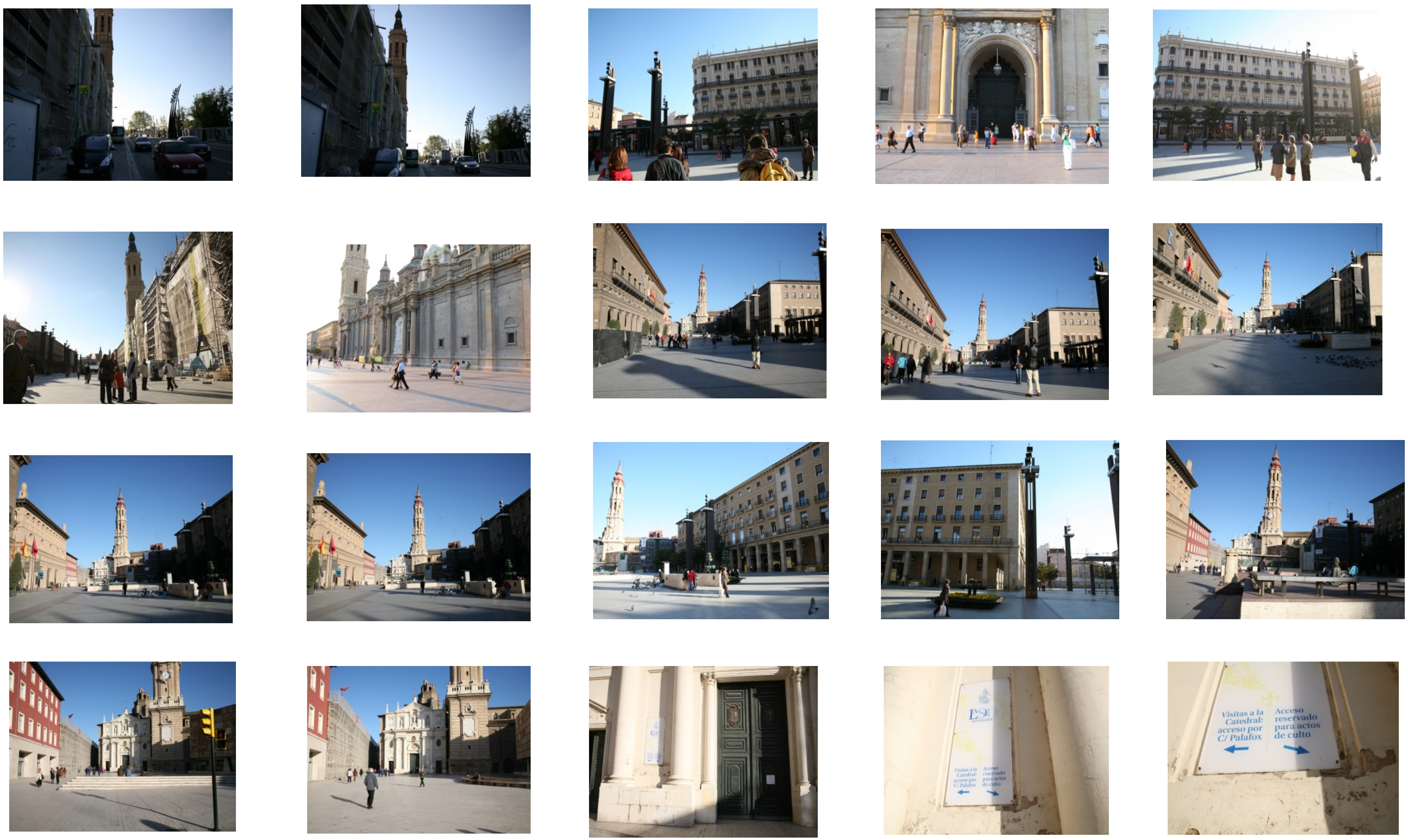
Motivation


Visitas a la Catedral: acceso por C/ Palafox
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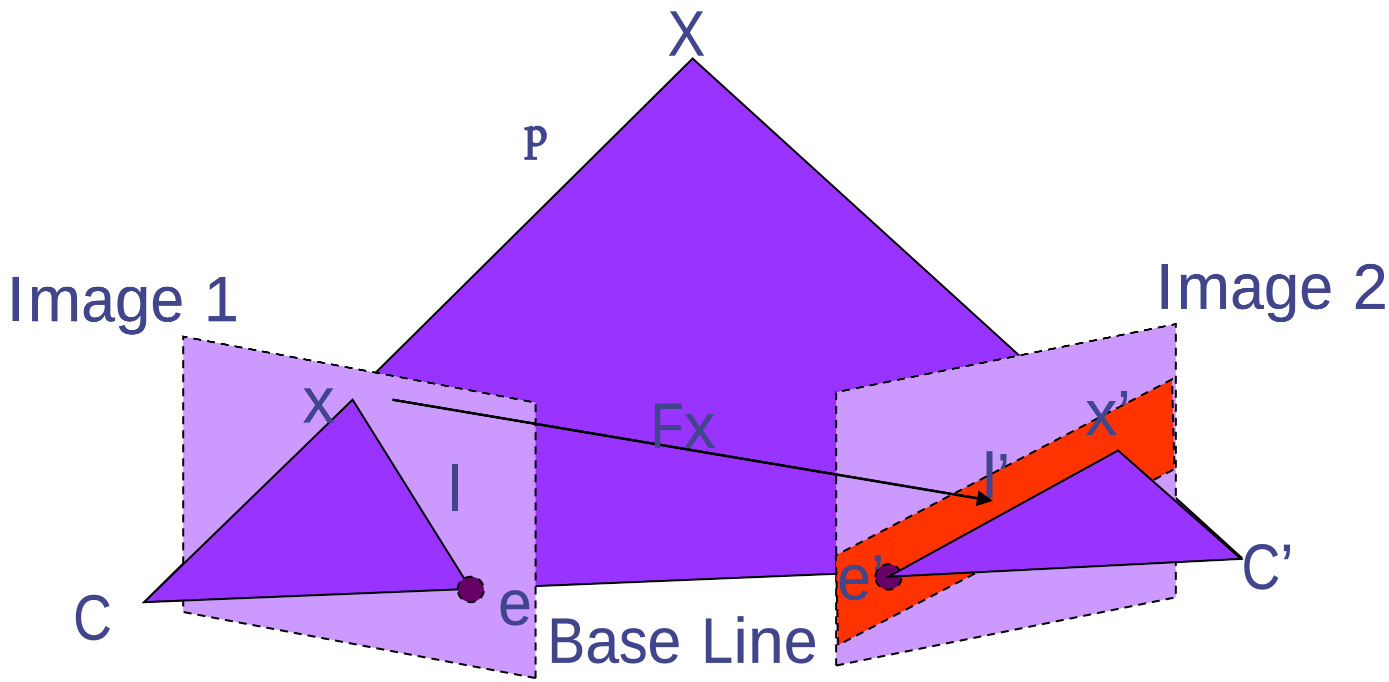
- Long term navigation using **epipolar geometry**

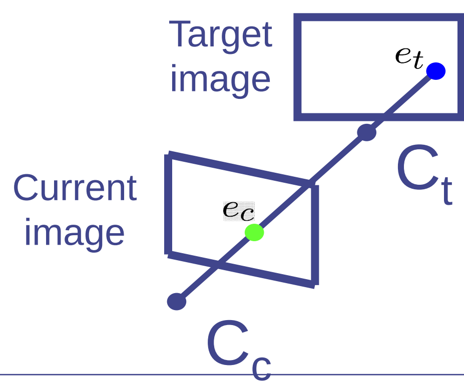
- Multi-robot control using **homography**
  - **One / Several cameras**

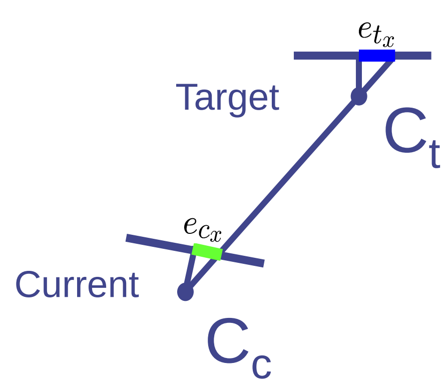
“Visual control” using

“Geometric constraints”

Long term navigation

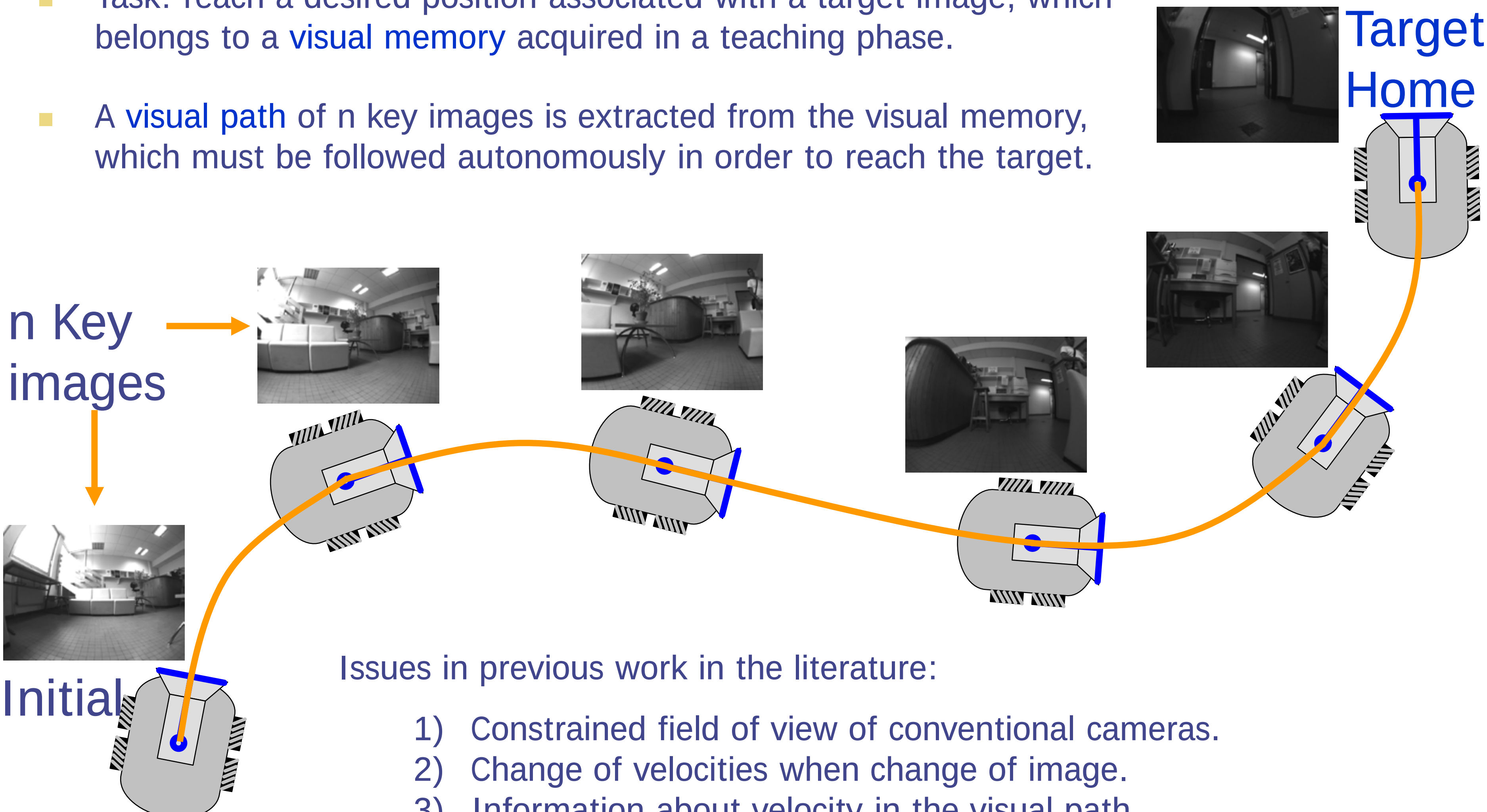






Long term navigation

- Task: reach a desired position associated with a target image, which belongs to a visual memory acquired in a teaching phase.
- A visual path of n key images is extracted from the visual memory, which must be followed autonomously in order to reach the target.

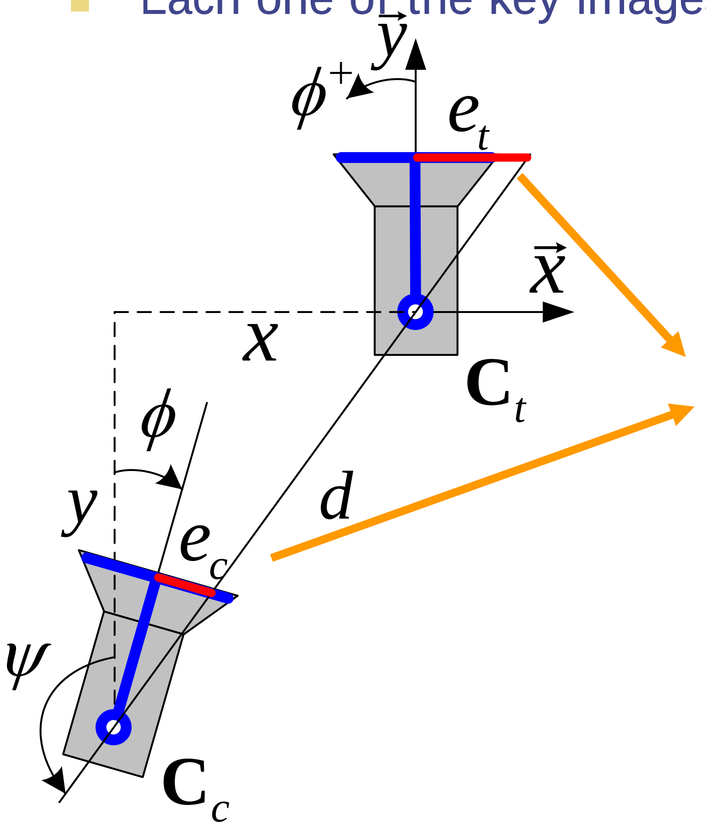


Issues in previous work in the literature:

1) Constrained field of view of conventional cameras.
2) Change of velocities when change of image.
3) Information about velocity in the visual path.

Long term navigation

- The omnidirectional cameras can be virtually represented as conventional cameras when working with points on the sphere.
- Each one of the key images is used as target image accordingly.



Target location $\Rightarrow$ $\mathbf{C}_t = (0,0,0)$

Current location $\Rightarrow$ $\mathbf{C}_c = (x, y, \phi)$

Epipoles
$$\begin{cases} e_c = \alpha_x \dfrac{x\cos\phi + y\sin\phi}{y\cos\phi - x\sin\phi}, \\ e_t = \alpha_x \dfrac{x}{y}. \end{cases}$$

- Interaction with the robot velocities:

$$\dot{e}_c = -\frac{\alpha_x \sin(\phi-\psi)}{d\cos^2(\phi-\psi)}\upsilon + \frac{\alpha_x}{\cos^2(\phi-\psi)}\omega,$$

$$\dot{e}_t = -\frac{\alpha_x \sin(\phi-\psi)}{d\cos^2(\psi)}\upsilon$$

Long term navigation

- Let us define a tracking error to drive the epipole smoothly to zero for every segment between key images

$$\zeta_{ce} = e_c - e_c^d(t) = 0.$$

where $e_c^d(t) = \frac{e_c(0)}{2}\left(1+\cos\left(\frac{\pi}{\tau}t\right)\right), 0 \le t \le \tau$ with $\tau = \frac{d_{\min}}{\upsilon}.$

$$e_c^d(t) = 0, \qquad t > \tau$$

- Control goal – Stabilization of the error system:

$$\dot{\zeta}_{ce} = -\frac{\alpha_x \sin(\phi-\psi)}{d\cos^2(\phi-\psi)}\upsilon + \frac{\alpha_x}{\cos^2(\phi-\psi)}\omega_{rt}^{ce} - \dot{e}_c^d.$$

- Considering that the translational velocity is known, the following rotational velocity, referred as reference tracking (RT) control, stabilizes the error system

$$\omega_{rt}^{ce} = \frac{\sin(\phi-\psi)}{d}\upsilon + \frac{\cos^2(\phi-\psi)}{\alpha_x}\left(\dot{e}_c^d - k_c\zeta_{ce}\right).$$

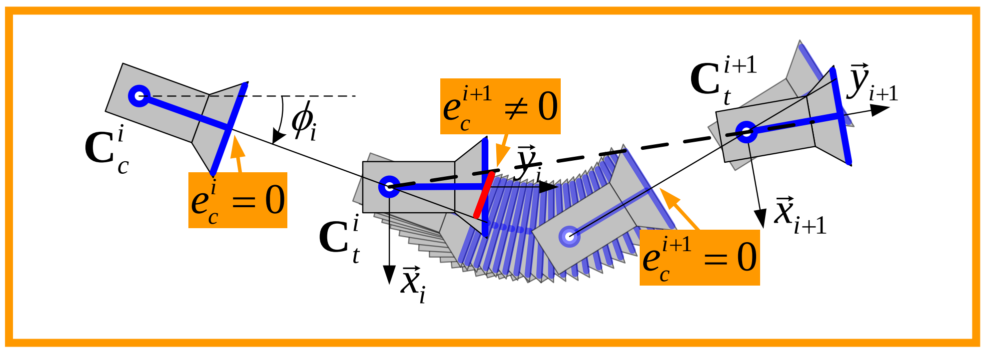
with $k_c > 0$.

Long term navigation

- The current epipole gives information of the translation direction and it is directly related to the required robot rotation to be aligned with the target.
- Use of the *x*-coordinate of the current epipole as feedback information to control the robot heading and so, to correct the lateral deviation.

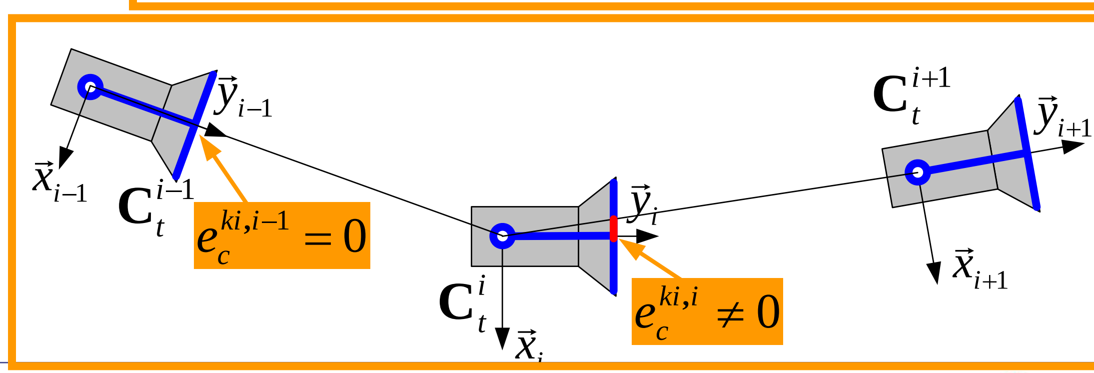
Non-null translational velocity $\boxed{\upsilon \neq 0}$ Rotational velocity $\omega^{ce} = k_t \omega_{rt}^{ce} + \overline{\omega}^{ce}$

First component of the rotational velocity



$\omega \Rightarrow f(e_c)$

Second component of the rotational velocity



$\omega \Rightarrow f(e_c^{ki})$

Long term navigation

- A varying translational velocity according to the shape of the path can be computed depending on the epipoles between key images.

$$\upsilon^{ce} = \upsilon_{\mathbf{max}} + \upsilon_{\mathbf{min}} + \frac{\upsilon_{\mathbf{max}} - \upsilon_{\mathbf{min}}}{2} \mathbf{tanh}\left(1 - \frac{\left|e_c^{ki} / d_{\mathbf{min}}\right|}{\sigma}\right).$$

$$\tau = \frac{d_{\min}}{\upsilon}$$

- We propose the following nominal rotational velocity, which is computed from the epipoles between key images:

$$\overline{\omega}^{ce} = \frac{k_m \upsilon^{ce}}{d_{\mathbf{min}}} e_c^{ki}.$$

- So that, the complete rotational velocity (RT+ control) is given as:

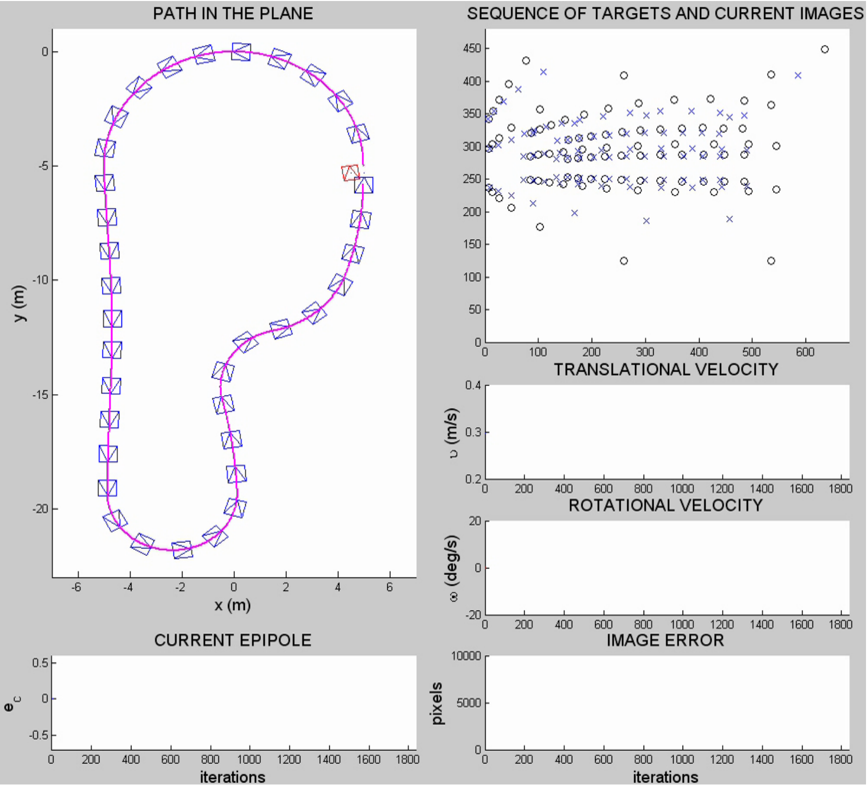
$$\omega^{ce} = k_t \omega_{rt}^{ce} + \overline{\omega}^{ce}.$$

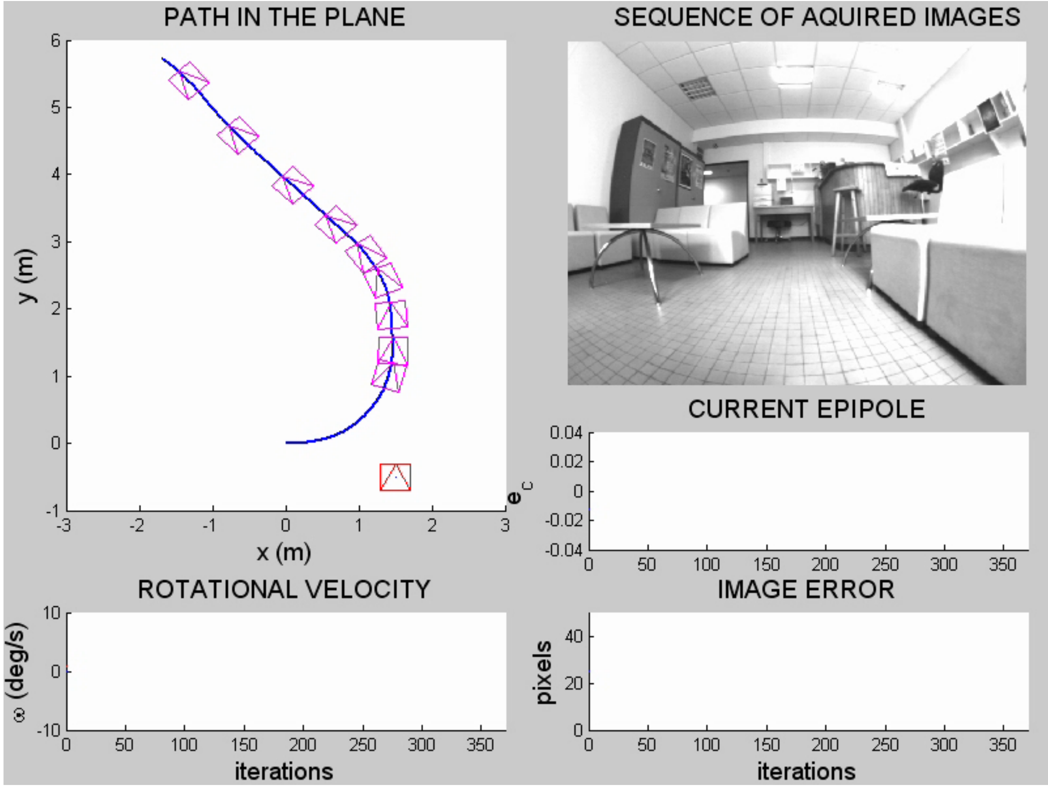
Switching and stop condition

- The switching condition to the next key image or to stop the task is given when the image error starts to increase, which is defined as follows:

$$\varepsilon = \frac{1}{r} \sum_{j=1}^{r} \left\| \mathbf{p}_j - \mathbf{p}_{i,j} \right\|.$$

Long term navigation





Wheeled mobile robots navigation from a visual memory using wide field of view cameras, H.M. Becerra, J. Courbon, Y. Mezouar, C. Sagues, IEEE/RSJ Int. Conference on Intelligent Robots and Systems (IROS'10), pages 5693-5699, Taipei, Taiwan, October 18-22, 2010

Visual navigation of wheeled mobile robots using direct feedback of a geometric constraint
H.M. Becerra, C. Sagues, Y. Mezouar, J.-B. Hayet, Autonomous Robots, (ISSN 0929-5593), d.o.i. 10.1007/s10514-014-9382-3, Vol. 37(2):137-156 , 2014.

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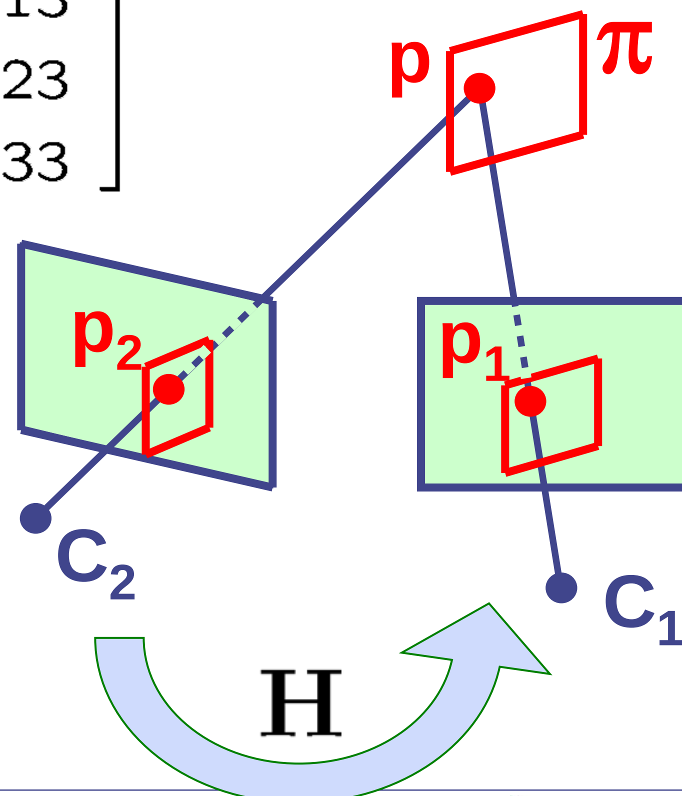
“Visual control” using

“Geometric constraints”

Multi robot control with flying camera (H)

- Homography: Projective transformation relating the projections in two perspective images of points belonging to a scene plane

$$\mathbf{p}_2 = \mathbf{H}\,\mathbf{p}_1 \qquad \mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix}$$



- Can be computed linearly (least squares) from four point matches
- Gives the motion (rotation R and translation T) between the cameras:

$$\boxed{\mathbf{H} = \mathbf{R} + \mathbf{T}\,\mathbf{n}^T/d}$$

Plane: $(\mathbf{n},\ d)$

Multi robot control with flying camera (H)

- What? Visual control of mobile robots
  - Desired configuration defined by an image
  - Task: Navigate to the desired configuration

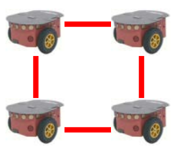
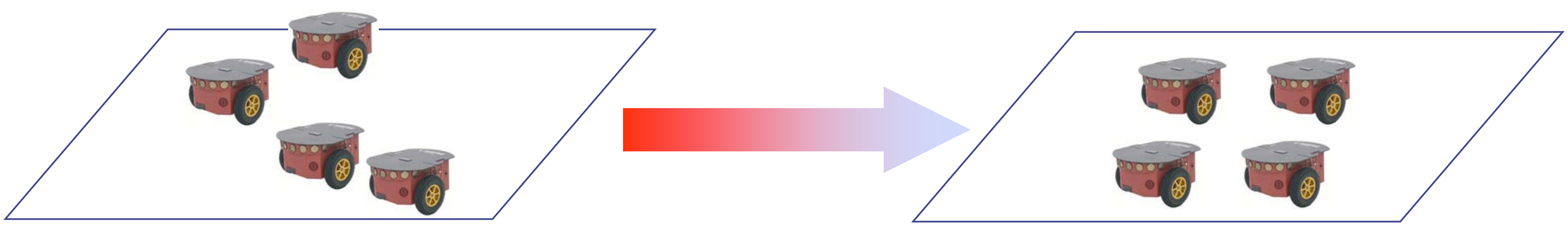


Image of desired configuration



Initial configuration

Desired configuration

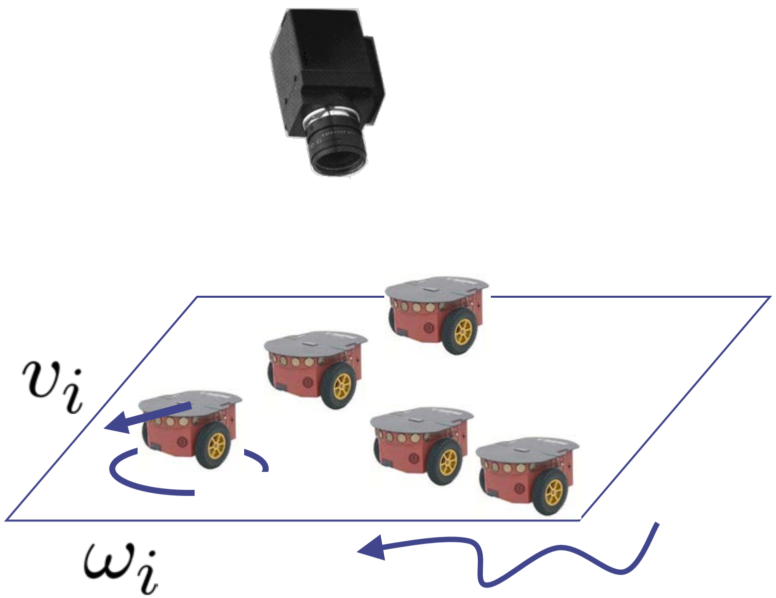
Multi robot control with flying camera (H)

- What? Visual control of mobile robots
- Who? Set of nonholonomic vehicles
  - Nonholonomic kinematics
    - Cartesian coordinates

$$\dot{x} = -v \sin\phi$$
$$\dot{y} = v \cos\phi$$
$$\dot{\phi} = \omega$$

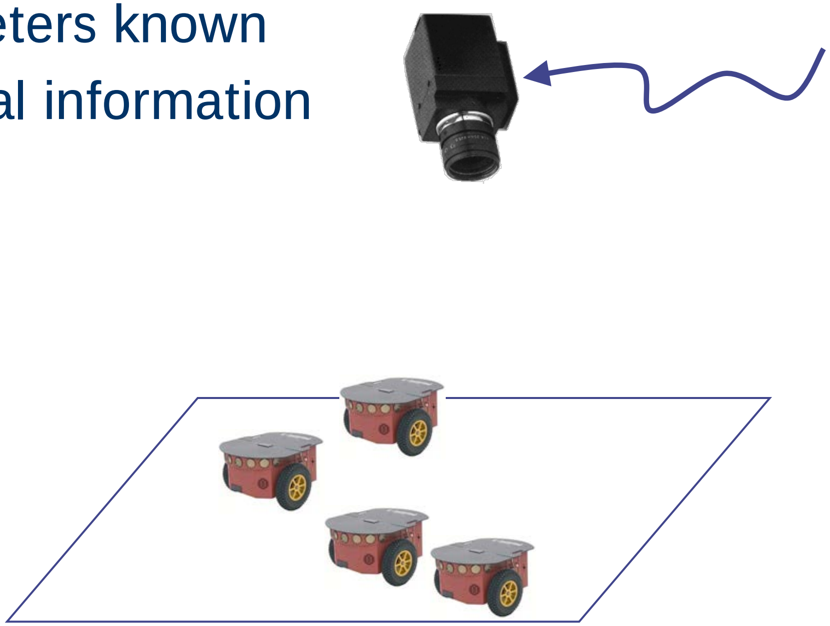
    - Polar coordinates

$$\dot{\rho} = v \cos\alpha$$
$$\dot{\alpha} = \omega - \frac{v}{\rho}\sin\alpha$$
$$\dot{\phi} = \omega$$



Multi robot control with flying camera (H)

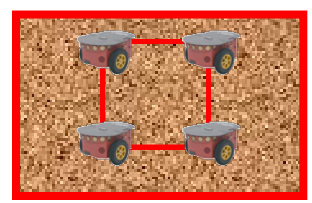
- What? Visual control of mobile robots
- Who? Set of nonholonomic vehicles
- How? Flying camera
  - Flying camera looking downward
  - Camera motion unknown
  - Intrinsic camera parameters known
  - Homography: Only visual information



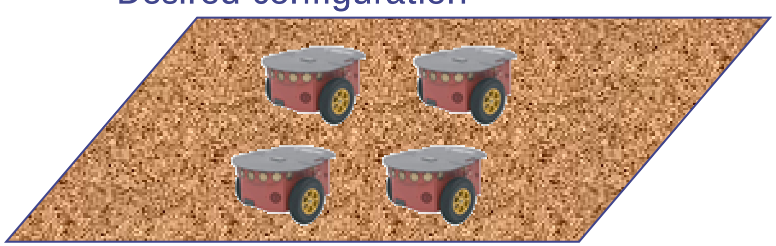
Multi robot control with flying camera (H)

- What? Visual control of mobile robots
- Who? Set of nonholonomic vehicles
- How? Flying camera
- Where? Motion occurs in a planar floor
  - This gives additional constraints on the homography
  - Only the set of robots may remain common in the scene

Image of desired configuration:



Desired configuration



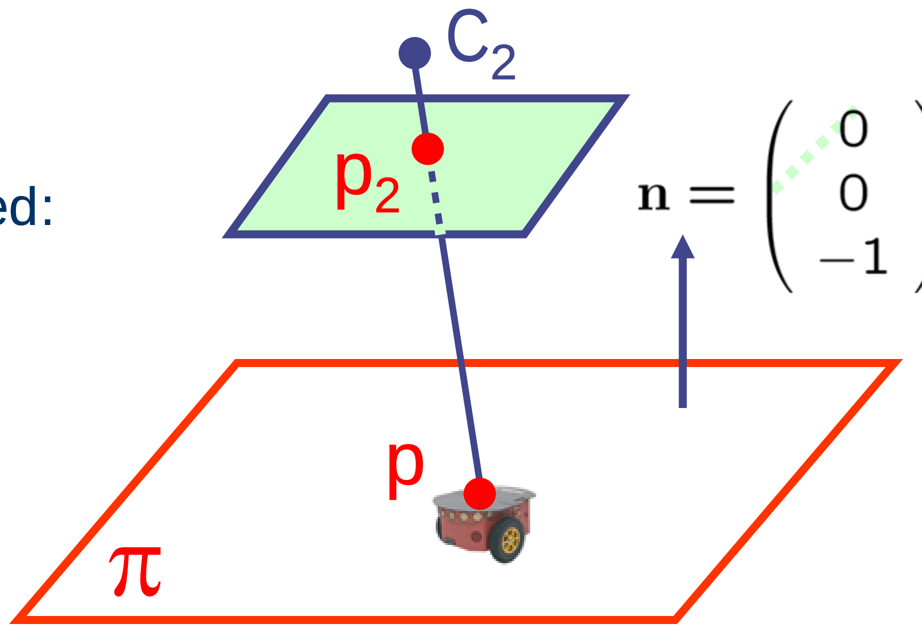
Actual configuration

Multi robot control with flying camera (H)

- The homography in our framework:
  - Multi-robot motion in a planar floor
  - Points = Robots => Homography
  - Camera flies parallel to the floor
- Then, the homography is constrained:

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{H} = \begin{bmatrix} \cos\phi & \sin\phi & -t_x/d \\ -\sin\phi & \cos\phi & -t_y/d \\ 0 & 0 & 1 \end{bmatrix}$$



$$\mathbf{n} = \begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix}$$

- This homography can be computed from a minimal set of two points/robots

Multi robot control with flying camera (H)

$$\mathbf{H}_{rigid}$$

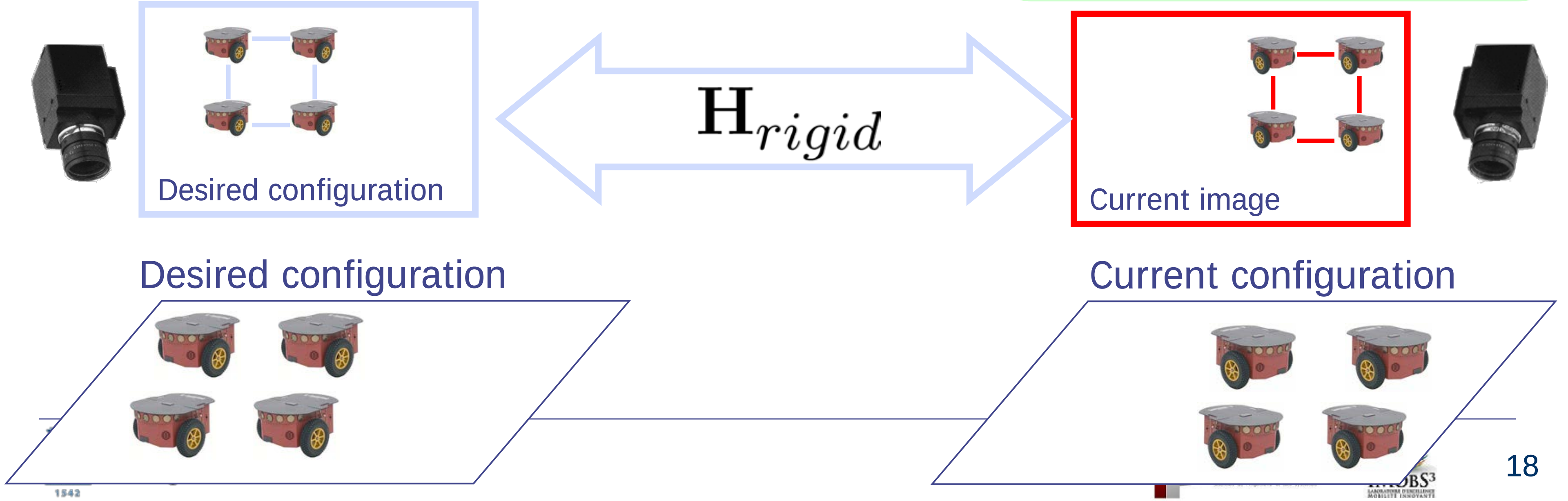
- If the robots are in the desired configuration:
  - The homography is conjugate to a planar Euclidean transformation
  - The homography is not the identity matrix

$$\mathbf{H}_{rigid} = \begin{bmatrix} \cos\phi & \sin\phi & h_{13} \\ -\sin\phi & \cos\phi & h_{23} \\ 0 & 0 & 1 \end{bmatrix}$$

Extracting Motion parameters

$$\mathbf{n} = (0, 0, -1)^T$$
$$\mathbf{x} = (x, y, 0)^T$$

Which is coherent with a rigid motion. So, the robots are in the desired formation



Multi robot control with flying camera (H)

$$\mathbf{H}_{nonrigid}$$

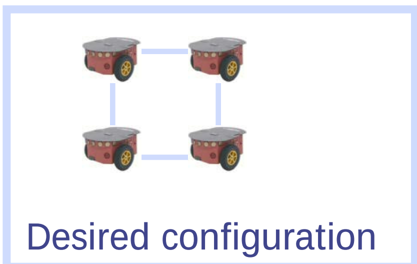
- If the robots are NOT in the desired configuration:
  - The homography is a similarity transformation with isotropic scaling s
  - The H computation with the 2-point method

$$\mathbf{H}_{nonrigid} = \begin{bmatrix} s\cos\phi & s\sin\phi & h_{13} \\ -s\sin\phi & s\cos\phi & h_{23} \\ 0 & 0 & 1 \end{bmatrix}$$

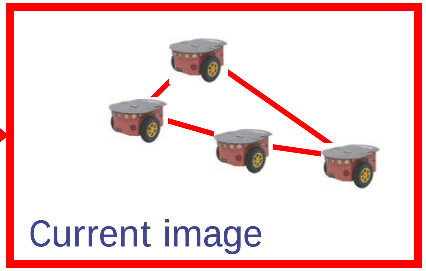
Extracting Motion parameters

$$\mathbf{n} = (0, 0, -1)^T$$
$$\mathbf{x} = (x, y, \underline{(s-1)d^2})^T$$

Which is NOT coherent with a rigid motion. So, the robots are not in formation



$$\mathbf{H}_{nonrigid}$$



Desired configuration

Current configuration

Multi robot control with flying camera (H)

$$\mathbf{H}_{nonrigid} \xrightarrow{\text{controller}} \mathbf{H}_{rigid}$$

- We have
  - Robots not in formation
  - Nonrigid homography
  - Each pair of robots induces a different Homography, valid but not coherent

$$\mathbf{H}_{nonrigid} = \begin{bmatrix} s\cos\phi & s\sin\phi & h_{13} \\ -s\sin\phi & s\cos\phi & h_{23} \\ 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{p}' = \mathbf{H}_{nonrigid}\,\mathbf{p}$$

- We want
  - Robots in formation
  - Rigid homography
  - Every pair of robots induce the same Homography

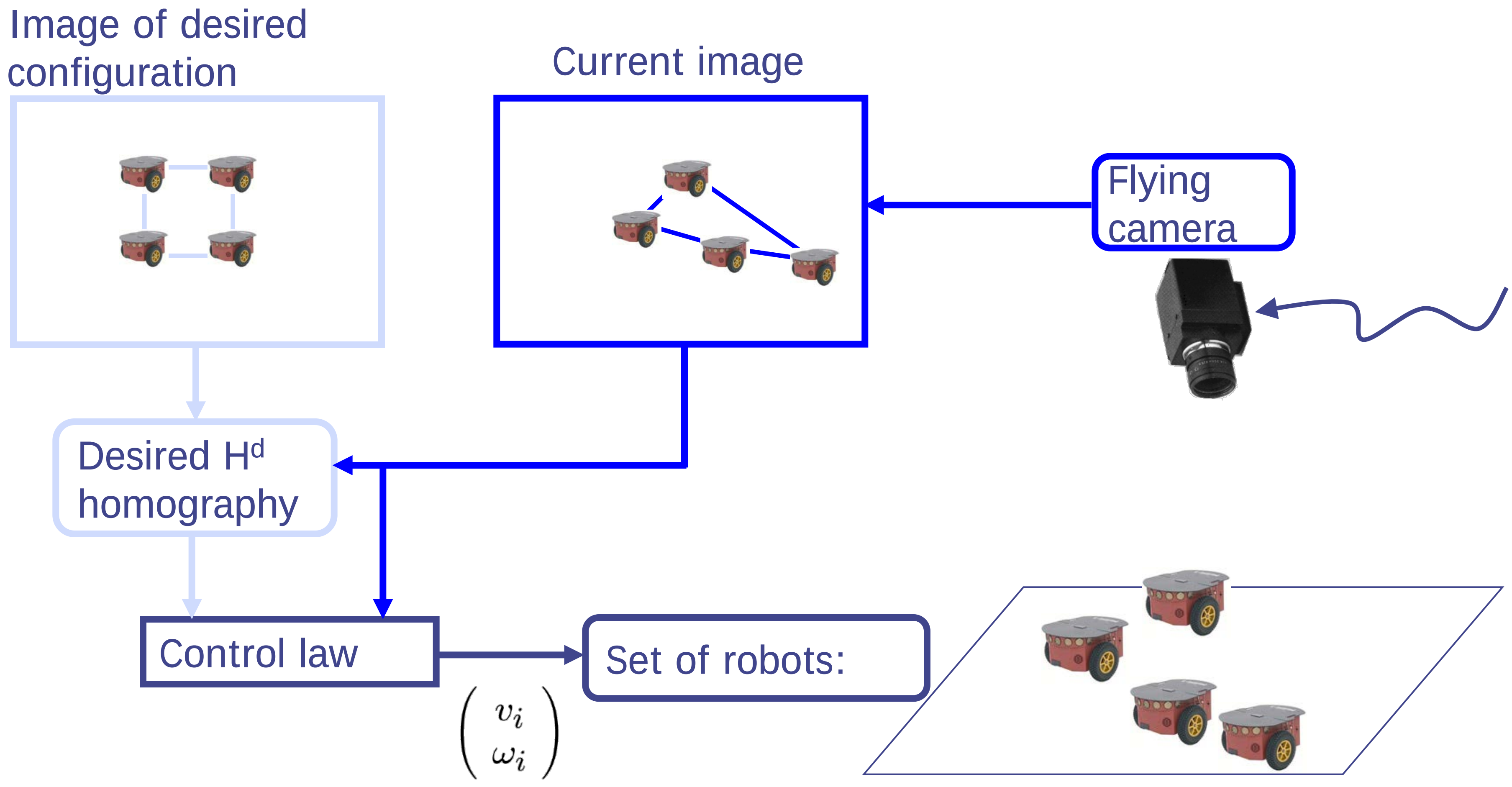
$$\mathbf{H}_{rigid} = \begin{bmatrix} \cos\phi & \sin\phi & h_{13} \\ -\sin\phi & \cos\phi & h_{23} \\ 0 & 0 & 1 \end{bmatrix}$$

- We define a desired homography
  - Like the nonrigid homography but being induced by keeping the motion constraints
  - The task is to drive the robots to the desired homography
  - The desired homography is not constant and depends on the robots and camera motion

$$\mathbf{H}^d = \mathbf{H}_{nonrigid} \begin{bmatrix} 1/s & 0 & 0 \\ 0 & 1/s & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

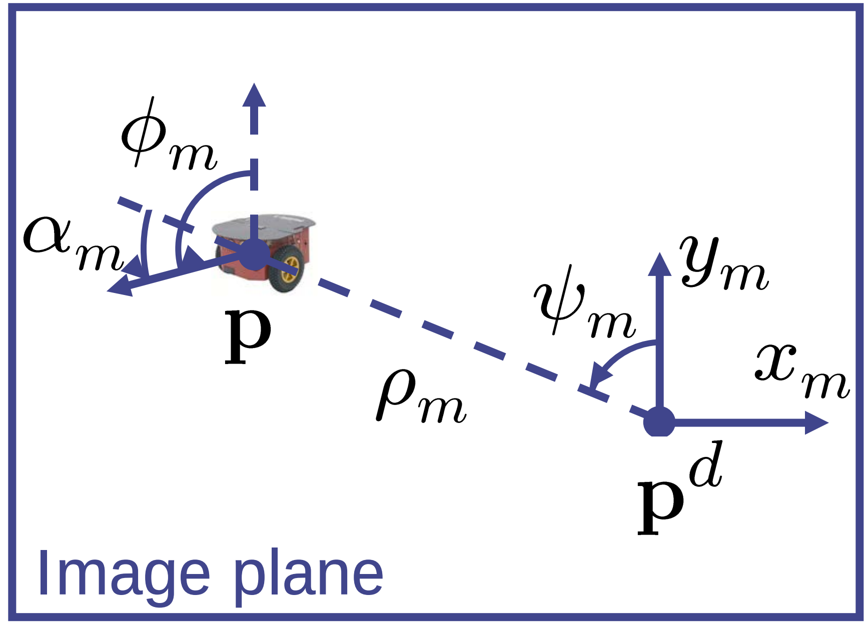
$$\mathbf{p}^d = (\mathbf{H}^d)^{-1}\,\mathbf{p}'$$

Multi robot control with flying camera (H)



Multi robot control with flying camera (H)

- Image-based control law
- Control error:
  - Current state of the robots on the image vs desired states given by the desired homography
- Switched control consisting of three sequential steps:



$$\text{Step 1}\begin{cases} v = 0 \\ \omega = \dot{\psi}_c - k_\omega\,(\alpha_m - \pi) \end{cases}$$

$$\text{Step 2}\begin{cases} v = \dot{\rho}_d - k_v\,\rho_m \\ \omega = \dot{\psi}_c - k_\omega\,(\alpha_m - \pi) \end{cases}$$

$$\text{Step 3}\begin{cases} v = 0 \\ \omega = -k_\omega\left((\phi_m - \psi_{Fm}) - (\phi_m^0 - \psi_{Fm}^0)\right) \end{cases}$$

$$\rho_m = \sqrt{(p_x - p_x^d)^2 + (p_y - p_y^d)^2}$$

$$\psi_m = atan2\left(-(p_x - p_x^d), (p_y - p_y^d)\right)$$

$$\psi_{Fm} = atan2\left(-(p_x^i - p_x^j), (p_y^i - p_y^j)\right)$$

$$\mathbf{x}^d(t) = (x^d, y^d, \phi^d)^T$$

$$\dot{\rho}_d = \partial\rho_c / \partial\mathbf{x}^d$$

$$\phi_m = \text{atan2}(-\Delta p_x, \Delta p_y)$$

$$\alpha_m = \phi_m - \psi_m$$

Stability for the control can be demostrated

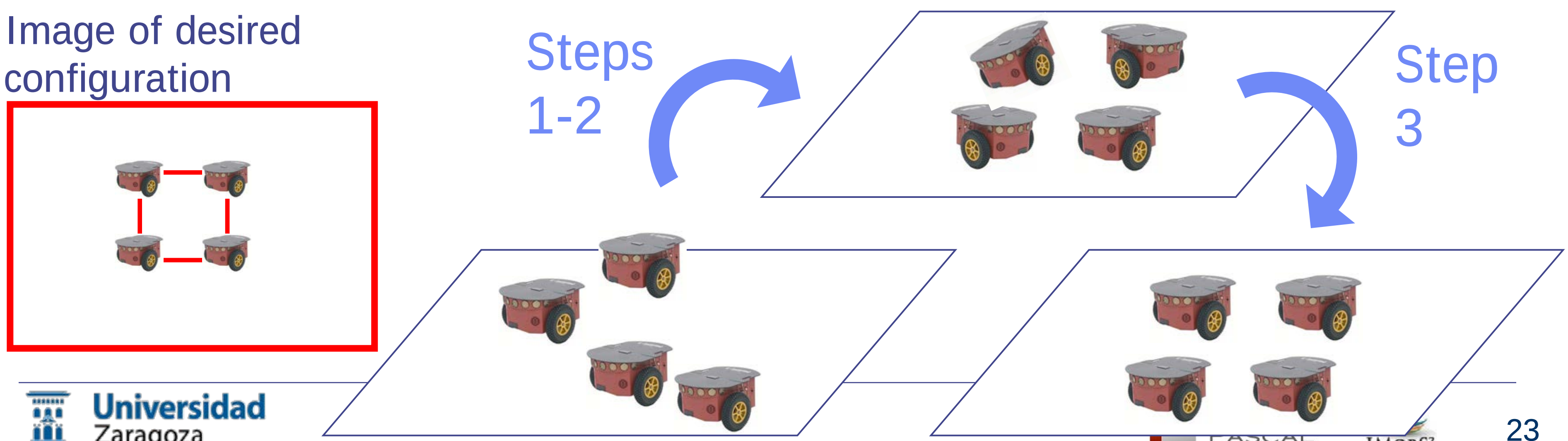
Multi robot control with flying camera (H)

- Steps 1-2 orientate and drive the robots toward their target locations. In practice, they are carried out simultaneously:

$$\text{Step 1 and 2} \begin{cases} v = \dot{\rho}_d - k_v\, \rho_m \\ \omega = \dot{\psi}_c - k_\omega\, (\alpha_m - \pi) \end{cases}$$

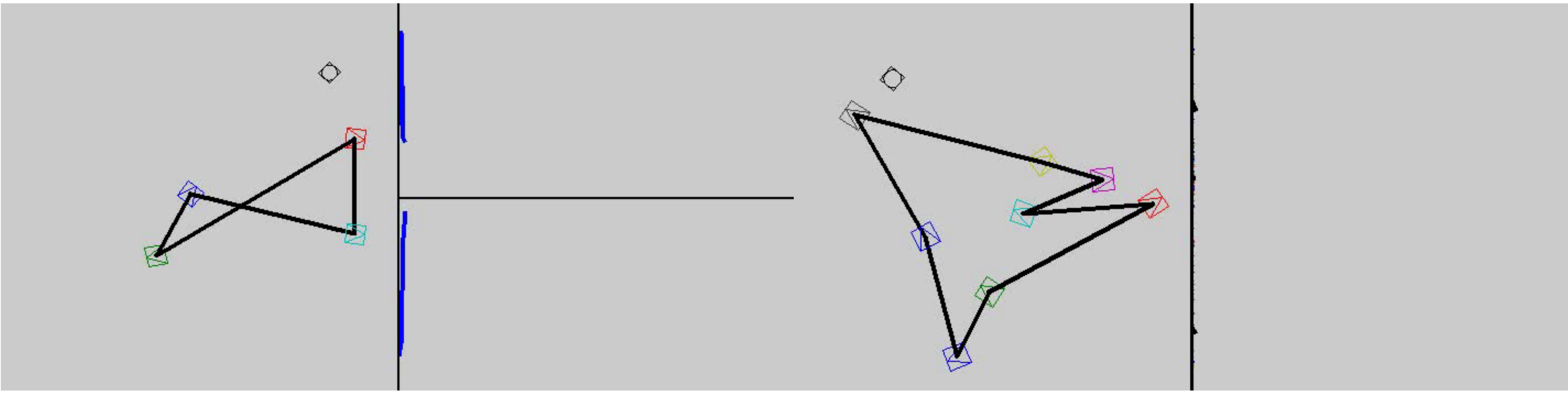
- Step 3 rotates the robots until they are in the required relative orientation within the formation

$$\text{Step 3} \begin{cases} v = 0 \\ \omega = -k_\omega\, \left((\phi_m - \psi_{Fm}) - (\phi_m^0 - \psi_{Fm}^0) \right) \end{cases}$$

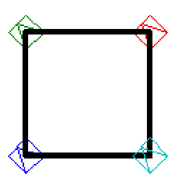


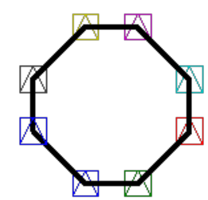
Multi robot control with flying camera (H)

Top view | Linear velocity: v | Top view | Homography entries

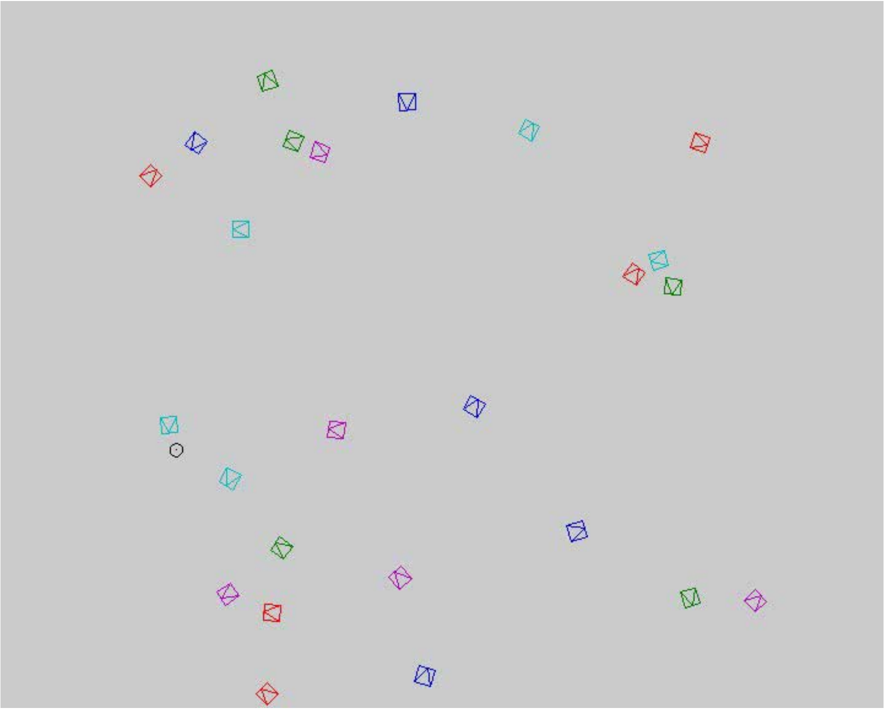


Angular velocity: ω

Desired configuration: 

Desired configuration: 

Multi robot control with flying camera (H)



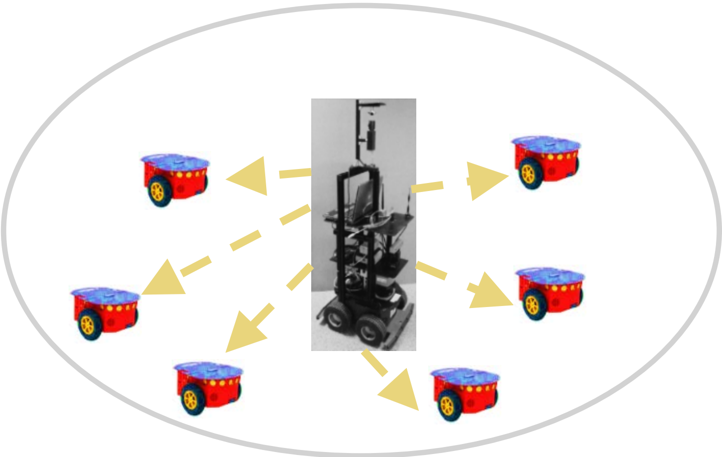
Homography-Based Multi-Robot Control with a Flying Camera, G. López-Nicolás, Y. Mezouar, C. Sagues, IEEE Int. Conference on Robotics and Automation (ICRA'11), pages 4492-4497, Shanghai-China, May 9-13, 2011.

Visual Control for Multi-Robot Organized Rendezvous, G. Lopez-Nicolas, M. Aranda, Y. Mezouar and C. Sagues, IEEE Transactions on Systems Man and Cybernetics: Part B. Vol.: 42(4):1155-1168, d.o.i. 10.1109/TSMCB.2012.2187639, 2012.

Multi robot control with multiple cameras (H)

Better performance:

- Minimization of sum squared distances current-desired position

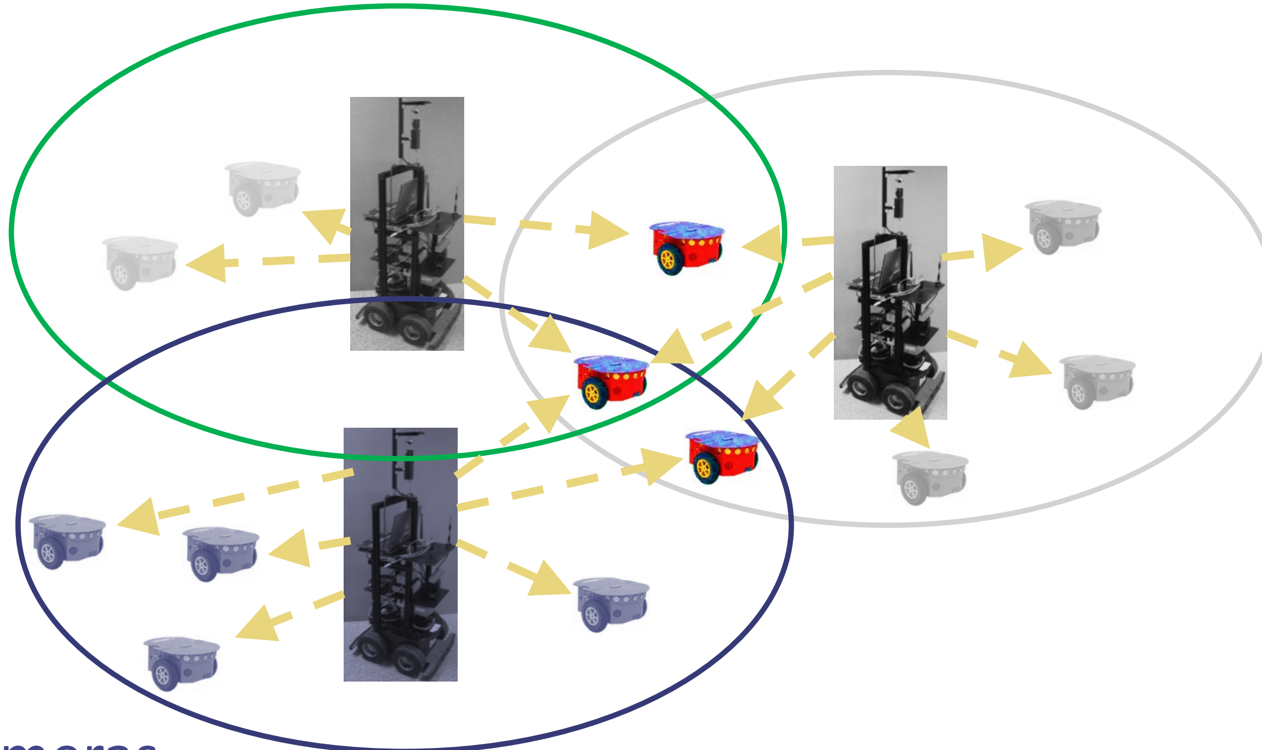


Several issues with the single-camera centralized method:

- Robustness (single point of failure)
- Sensing range (limited field of view)
- Scalability w.r.t. number of robots (processing and communications requirements)

Multiple cameras /Multiple robots

Multi robot control with multiple cameras (H)



- Omnidirectionas cameras
- Each camera is one controller
- Each camera controls a subset ot the team
- Distributed (partially)
- Comunication camera - Controlled robots
- No communication between cameras

Multi robot control with multiple cameras (H)

- We constrain the homography to have the form of a Euclidean 2D transformation, also called a rigid transformation:

$$\mathbf{H_e} = \begin{bmatrix} \cos\phi_e & \sin\phi_e & t_{xe} \\ -\sin\phi_e & \cos\phi_e & t_{ye} \\ 0 & 0 & 1 \end{bmatrix} \quad \left\{ \begin{array}{l} \mathbf{t} = (t_{xe}, t_{ye})^T \\ \phi_e \end{array} \right.$$

- Observe that:
  - ✓ The assumed planar camera motion can be explained by this homography as a translation and rotation
  - ✓ Any rigid motion w.r.t. the reference image is also accounted for by this homography
  - ✓ Then, the errors of this mapping of points must be due only to a nonrigid motion of the robots, i.e. the motion that separates the set from being in formation

Multi robot control with multiple cameras (H)

- Method outline:

1. Compute a least-squares Euclidean homography using the reference and current image points
2. Use it to map the reference points to a new set of *desired* points in the current image
3. Make the robots move so that the points in the current image coincide with the *desired* points

- We are not interested in computing the camera motion or any rigid motion of the robot set, only in isolating the effect of **nonrigid motions** of the group
- Note the camera can perform any **arbitrary planar motion**

Multi robot control with multiple cameras (H)

- We will move the robots so that their current image positions $\mathbf{p}$ will coincide with those ($\mathbf{p}^{\mathbf{d}}$) given by the homography mapping computed from $\mathbf{p}$ and the points of the desired configuration, $\mathbf{p}'$
- An objective of interest can be:

$$\mathbf{p}^{\mathbf{d}}(\mathbf{H}^{\mathbf{d}}, \mathbf{p}', \mathbf{p}) \ni S = \sum_{i=1}^{n} ||\mathbf{p_i} - \mathbf{p_i^d}||^2 \text{ is minimum}$$

A necessary condition is that the centroids of $\mathbf{p}$ and $\mathbf{p}^{\mathbf{d}}$ coincide:

$$\mathbf{p'_c} = \mathbf{p}' - \mathbf{c_{p'}} \;, \qquad \mathbf{p_c} = \mathbf{p} - \mathbf{c_p}$$

Multi robot control with multiple cameras (H)

◆ Then, we can simplify the homography parameterization:

$$\mathbf{H_r} = \begin{bmatrix} h^r_{11} & h^r_{12} & 0 \\ h^r_{21} & h^r_{22} & 0 \\ 0 & 0 & h^r_{33} \end{bmatrix} \sim \begin{bmatrix} \cos\phi_r & \sin\phi_r & 0 \\ -\sin\phi_r & \cos\phi_r & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{6}$$

- Constraints: $h^r_{11} = h^r_{22}\,,\qquad h^r_{12} = -h^r_{21}\,,\qquad {h^r_{11}}^2 + {h^r_{12}}^2 = 1$

- Considering only the two linear constraints:

$$\mathbf{H_l} = \begin{bmatrix} h^l_{11} & h^l_{12} & 0 \\ -h^l_{12} & h^l_{11} & 0 \\ 0 & 0 & h^l_{33} \end{bmatrix} \sim \begin{bmatrix} s\cos\phi_l & s\sin\phi_l & 0 \\ -s\sin\phi_l & s\cos\phi_l & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{8}$$

Multi robot control with multiple cameras (H)

- We show that the solution which provides the minimum squared distances for the robots can be obtained from the linearly constrained H

> *Proposition 1:* Let $\mathbf{p}'$ and $\mathbf{p}$ be two sets of n image points. Let $\mathbf{H_r}$ be the least-squares homography computed from $\mathbf{p}'$ and $\mathbf{p}$ having the form (6), and let $\mathbf{H_l}$ be the least-squares homography computed from $\mathbf{p}'$ and $\mathbf{p}$ having the form (8). Then, $\mathbf{H_r} = \mathbf{H_l} \cdot diag(1/s, 1/s, 0)$.

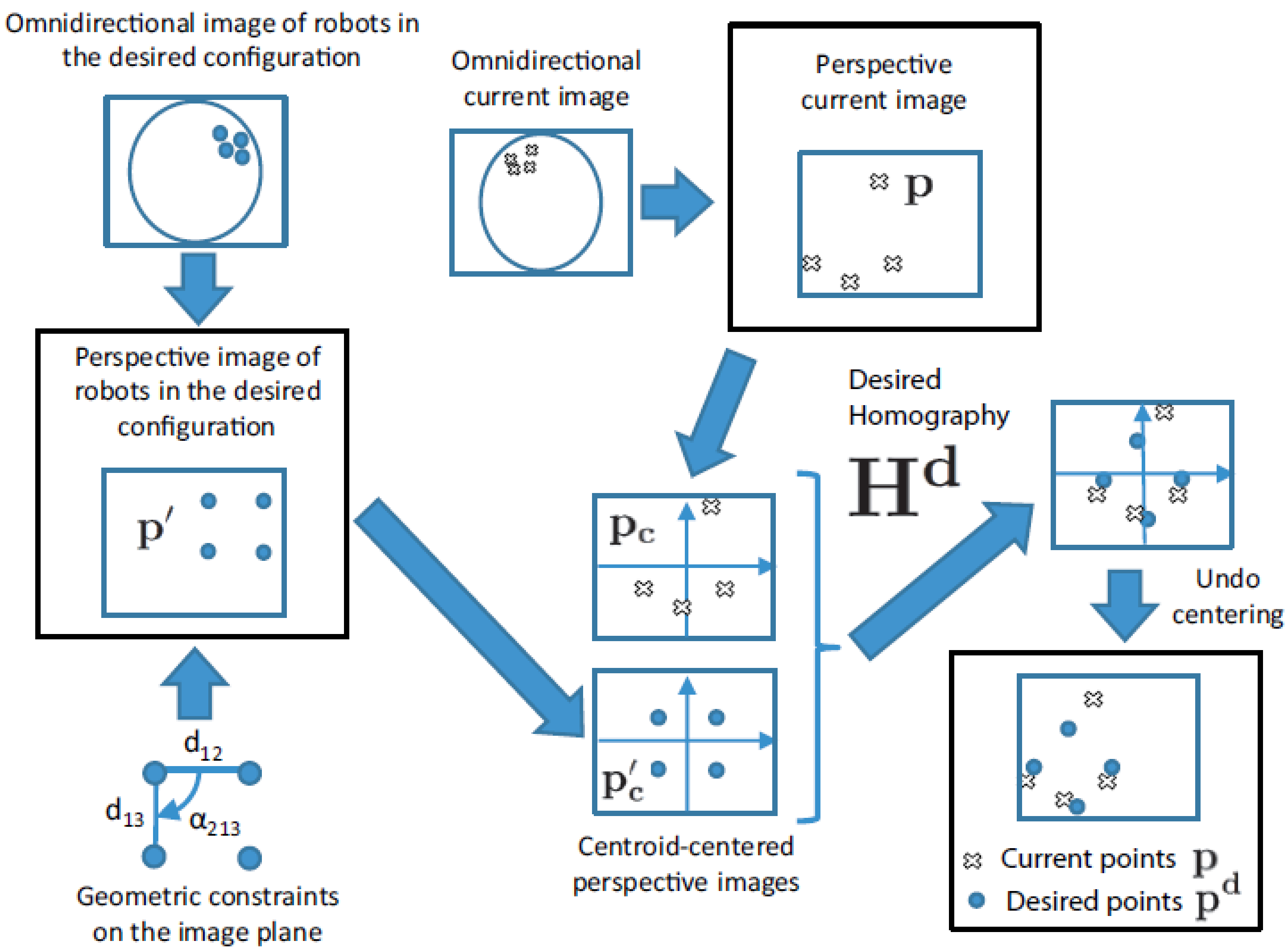
Multi robot control with multiple cameras (H)

- The solution is obtained efficiently: solving an overdetermined linear system with only one d.o.f.
- The desired image positions for the robots are then obtained from the computed homography ($H^d = Hr$):

$$Sr = \sum_{n=1}^{\infty} \left\| \mathrm{p_i} - \mathrm{p^d}_{\mathrm{ri}} \right\|^2 = \left({p_{xi}}'^2 + {p_{yi}}'^2\right) + \left({p_{xi}}^2 + {p_{yi}}^2\right) - 2[cos\phi_r\left({p_{xi}}'p_{xi} - {p_{yi}}'p_{yi}\right) + sin\phi_r({p_{yi}}'p_{xi} - {p_{xi}}'p_{yi})]$$

$$\boxed{\mathbf{p}^{\mathrm{d}} = \mathbf{H}^{\mathrm{d}}\mathbf{p}'_{\mathbf{c}} + \mathbf{c}_{\mathbf{p}}.}$$

Multi robot control with multiple cameras (H)

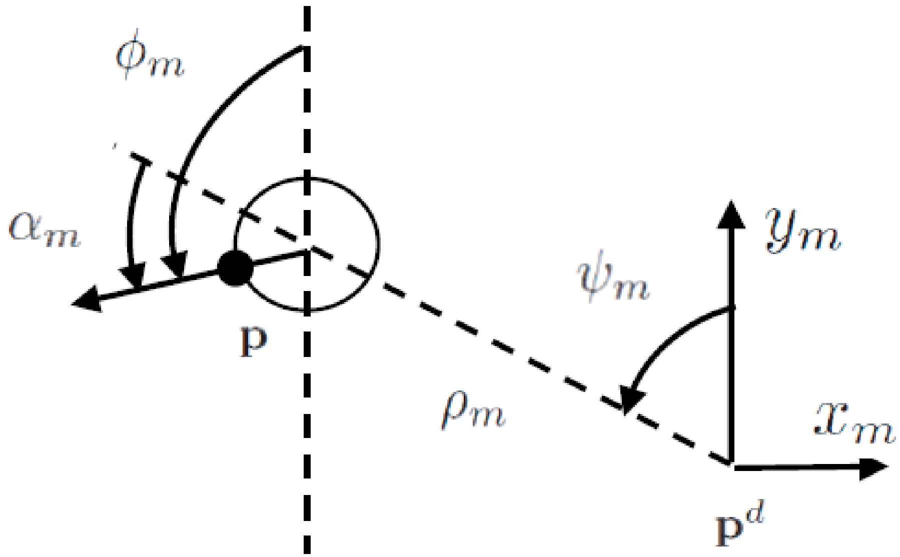


Multi robot control with multiple cameras (H)

- An image-based control law with proven local exponential stability is defined to drive each of the unicycle robots to its desired position:

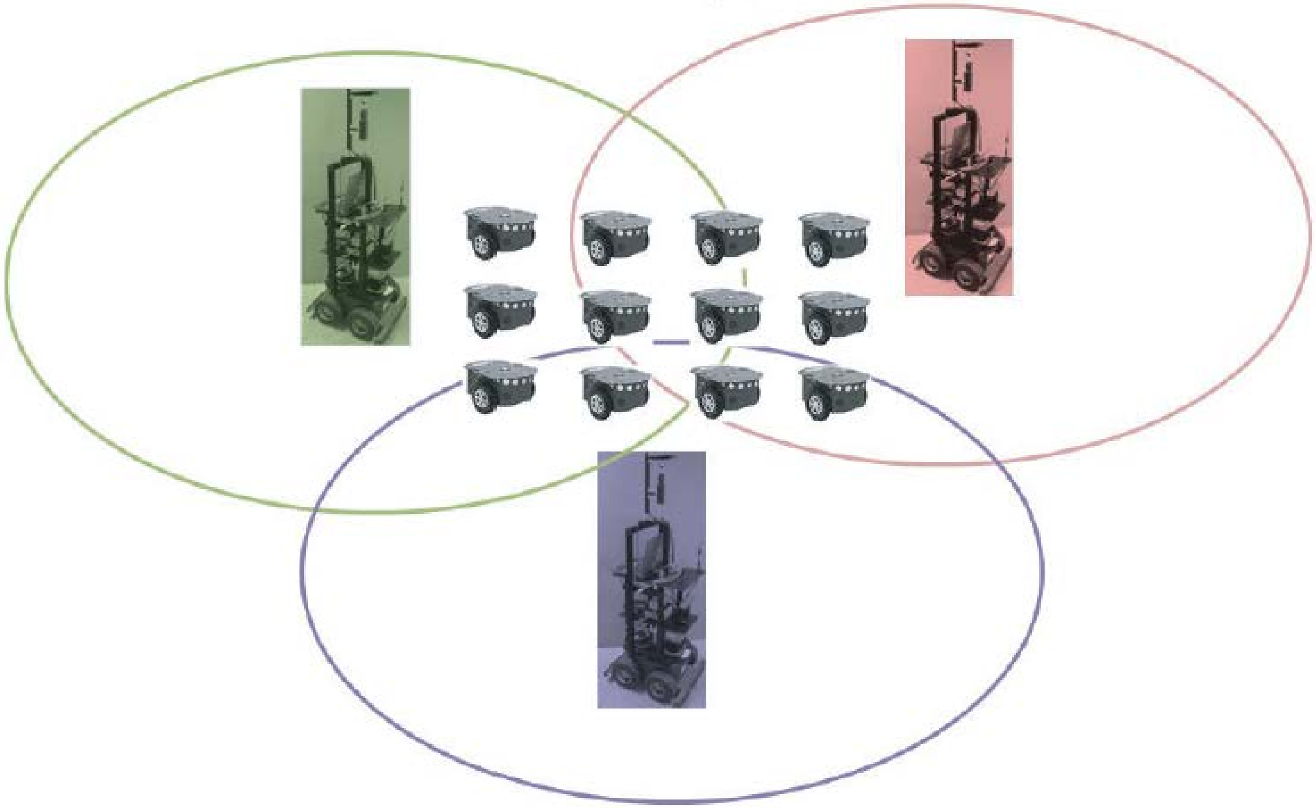
$$\boxed{\left\{ \begin{array}{l} v = -k_v \, sign(\cos\alpha_m)\, \rho_m \\ \omega = k_\omega \,(\alpha_d - \alpha_m) \end{array} \right.}$$

$$\alpha_d = \left\{ \begin{array}{lll} 0 & \text{if} & |\alpha_m| \leq \frac{\pi}{2} \\ \pi & \text{if} & |\alpha_m| > \frac{\pi}{2} \end{array} \right.$$



Multi robot control with multiple cameras (H)

- Overlaps betwen subsets are required.
- If every subset shares at least <u>two robots</u> with others, then convergence of the subsets implies convergence of the full set.



Multi robot control with multiple cameras (H)

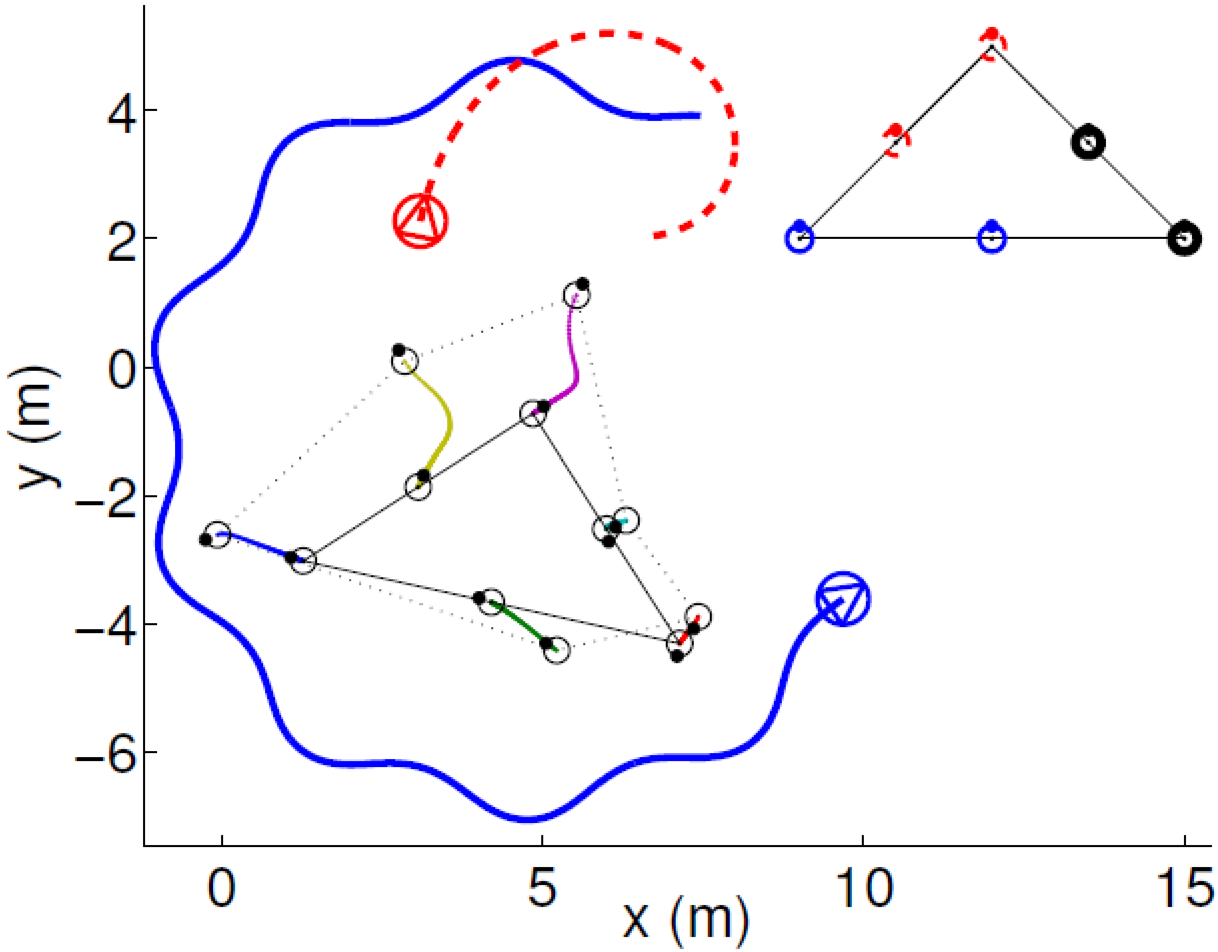
Behavior of a robot that receives multiple motion commands?

Different strategies:

- Select command with minimum linear velocity
- Compute the average of the commands
- Compute a weighted average to equalize the convergence of the different subsets

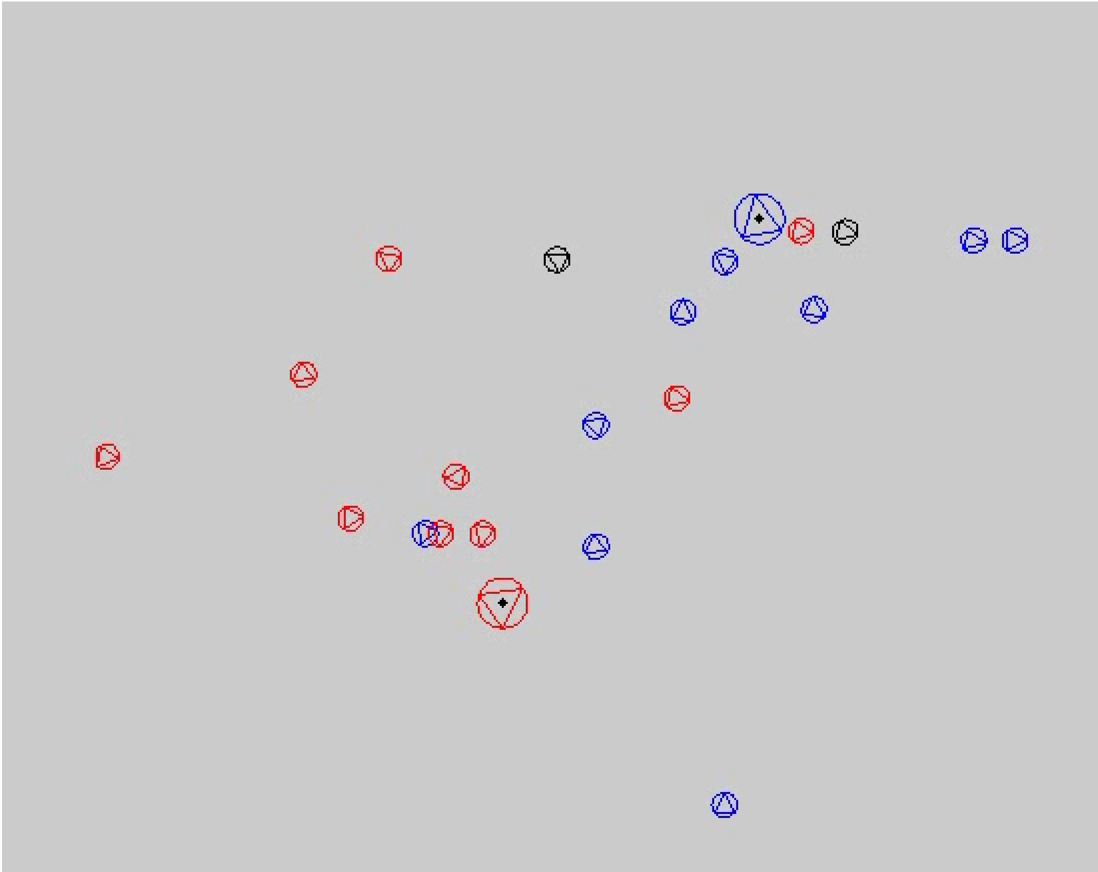
- All of these are observed to converge, through implicit coordination.
- No communication between the cameras/controllers is needed

Multi robot control with multiple cameras (H)

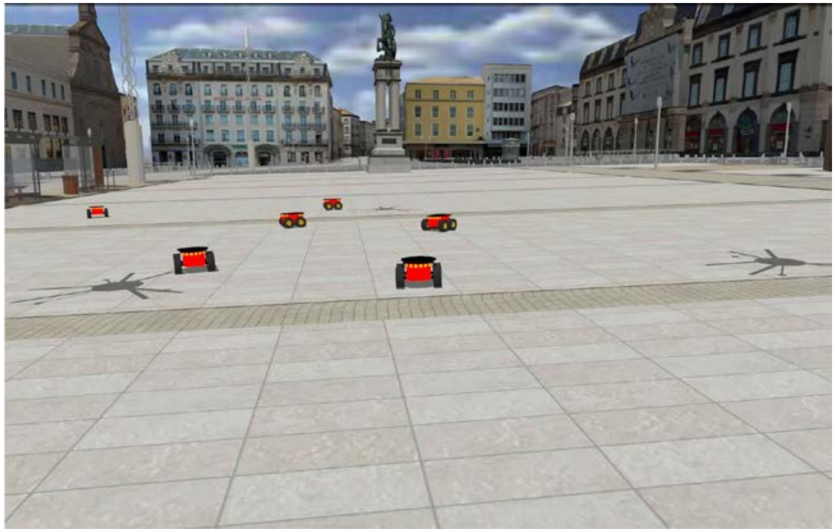


Multi robot control with multiple cameras (H)

- Multiple cameras
- Image based method which minimizes the sum of squared distances
- Partially distributed multi-robot solution for robot formation



Multi robot control with multiple cameras (H)



Hybrid multirobot control with multiple cameras, M. Aranda, Y. Mezouar, G. López-Nicolás, C. Sagüés, American Control Conference (ACC), IEEE – pages 6323-6329 (ISBN: 978-1-4799-0176-0), Washington DC, USA, 17-19 June 2013.

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