Autonomous docking of two marine robots: a vector field based approach

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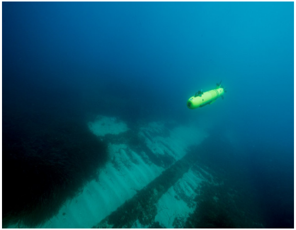
Overview I

Introduction

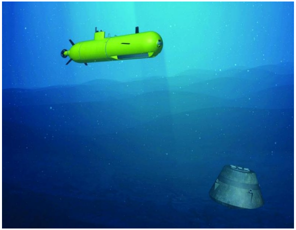
Examples of AUV operations

AUVs can be equipped with various types of sensors to perform different missions:

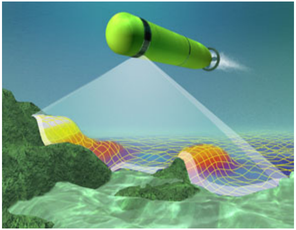
- Cameras for visual inspections
- Multibeam sonar for acoustic mapping/detection
- Magnetometers for magnetic mapping/detection



(a) ECA AUV inspecting a pipeline



(b) Thales AUV looking for underwater mines



(c) MBARI AUV mapping seafloor

AUV limitations

Figure: AUV deployment from a surface vessel (Courtesy of Subsea World News)

- Cost/duration of deployment/recovering of the AUV
- Limited battery life
- Limited storage capacity

Forssea's Remora

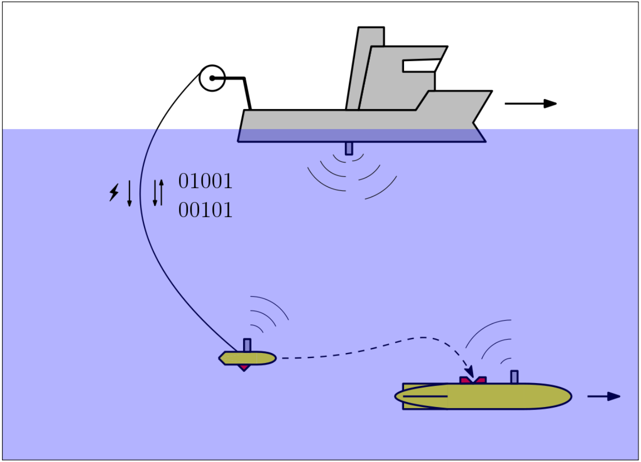


Figure: Autonomous dynamic docking of an ROV and an AUV

Problems from a control engineer's point of view

- The tether influence on the ROV's trajectory is unknown and quite unpredictable
- The targeted AUV is moving
- The ROV ought not crash onto fragile parts of the AUV
- The ROV ought not tie knots with its tether

Vector field based approach

Time-dependent attractive vector field

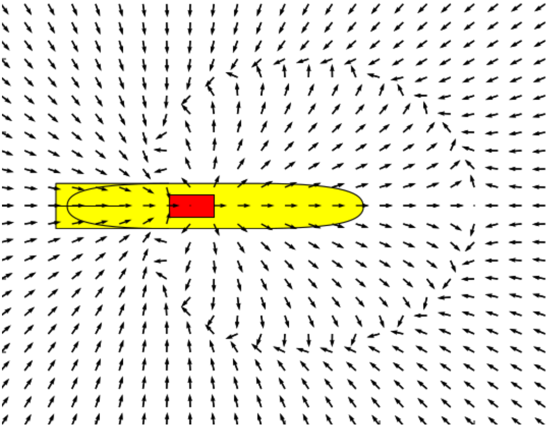


Figure: Attractive field generated by the targeted AUV

Method inspired from [Le Gallic et al., 2018], adapted for time-dependent vector fields.

Problem formalisation: frames

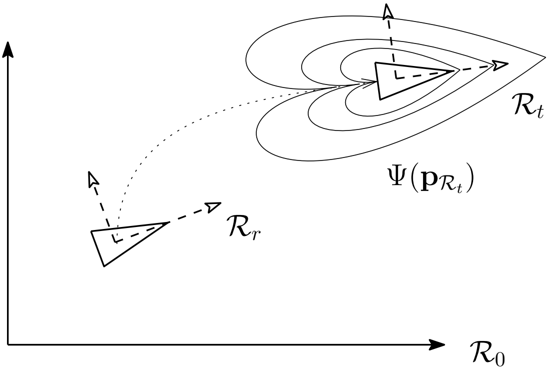


Figure: ROV, AUV, vector field and related frames

$$\boldsymbol{\Psi} : \mathbb{R}^3 \to \mathbb{R}^3$$
$$\mathbf{p} \mapsto \boldsymbol{\Psi}(\mathbf{p})$$

$\boldsymbol{\Psi}$ should be of class C^k, $k \geq n$, n being the relative degree of the robot's state model.

It is given in the $\mathcal{R}_t$ frame.

Problem formalisation: state model

Let us consider that the following variables are known:

- $\mathbf{x}_r = (\mathbf{p}_r, \mathbf{v}_{r,\mathcal{R}_r}, \boldsymbol{\xi})^{\mathrm{T}}$, state of the robot
- $\mathbf{p}_t$, $\mathbf{v}_t$, $\mathbf{a}_t$, $\boldsymbol{\xi}$, $\boldsymbol{\omega}_t$, $\dot{\boldsymbol{\omega}}_t$

And that we have a state model for the robot:

$$\dot{\mathbf{x}}_r = \mathbf{f}\left(\mathbf{x}_r, \mathbf{u}_r\right)$$

The goal is to find $\mathbf{u}_r$ so that the robot follows $\boldsymbol{\Psi}\left(\mathbf{p}_{r,\mathcal{R}_t}\right)$: the output vector $\mathbf{y}$ must be driven to $\mathbf{0}$.

$$\mathbf{y} = \begin{pmatrix} \mathbf{v}_r - \boldsymbol{\Psi}\left(\mathbf{p}_{r,\mathcal{R}_t}\right)_{\mathcal{R}_r} \\ \xi - \boldsymbol{\Xi}\left(\boldsymbol{\Psi}\left(\mathbf{p}_{r,\mathcal{R}_t}\right)_{\mathcal{R}_0}\right) \end{pmatrix}$$

Problem formalisation: Vector field transformation

The vector field $\mathbf{\Psi}\left(\mathbf{p}_{r,\mathcal{R}_t}\right)$ is given in the frame $\mathcal{R}_t$, but must be expressed in $\mathcal{R}_r$ to be used to drive the robot:

$$\mathbf{\Psi}\left(\mathbf{p}_{r,\mathcal{R}_t}\right)_{\mathcal{R}_r} = \mathbf{R}_r^{\mathrm{T}} \cdot \mathbf{\Psi}\left(\mathbf{p}_{r,\mathcal{R}_t}\right)_{\mathcal{R}_0}$$
$$\mathbf{\Psi}\left(\mathbf{p}_{r,\mathcal{R}_t}\right)_{\mathcal{R}_0} = \mathbf{R}_t \cdot \mathbf{\Psi}\left(\mathbf{p}_{r,\mathcal{R}_t}\right) + \mathbf{R}_t \cdot \mathbf{v}_t + \mathbf{Ad}\left(\omega_t\right) \cdot \left(\mathbf{p}_r - \mathbf{p}_t\right)$$

Problem formalisation: state-feedback linearisation

Using a state-feedback linearisation method ([Jaulin, 2015]), the command vector $\mathbf{u}_r$ can be computed as follows:

$$\mathbf{u}_r = \mathbf{A}^{-1}(\mathbf{x}_r) \cdot \left(\mathcal{E}\left(\mathbf{y} \dots \mathbf{y}^{(n-1)}\right) - \mathbf{b}(\mathbf{x}_r)\right)$$

where $\mathbf{y}^{(n)} = \mathcal{E}\left(\mathbf{y} \dots \mathbf{y}^{(n-1)}\right)$ is the chosen error dynamics equation.

State model: 2D holonomic robot

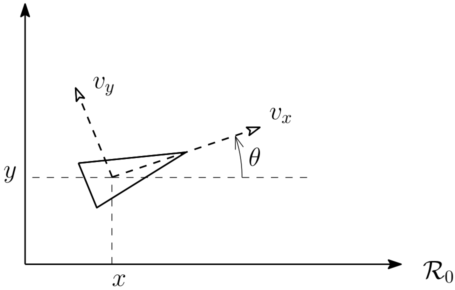


Figure: State model of the robot

Let us consider the following state model for our holonomic 2D robot:

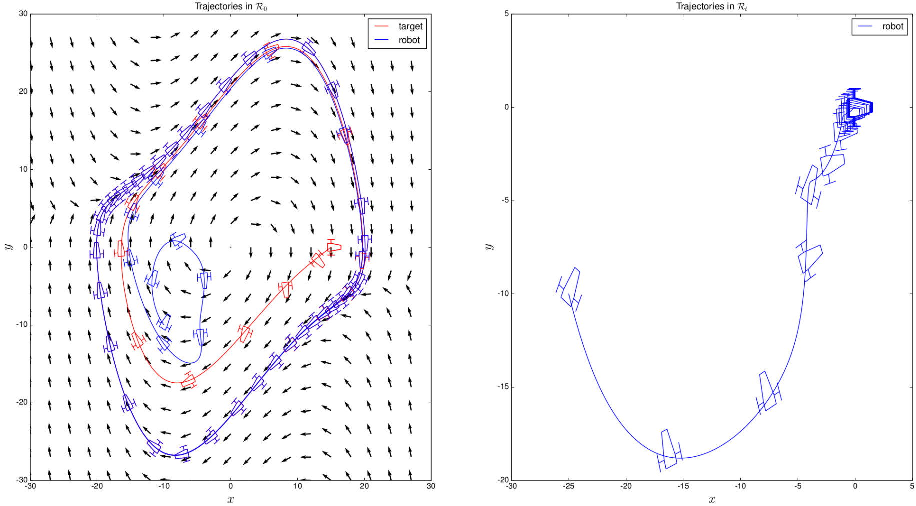
$$\mathbf{x} = (x, y, v_x, v_y, \theta)^{\mathrm{T}}$$

$$\dot{\mathbf{x}} = \begin{pmatrix} \mathbf{R}(\theta) \cdot \mathbf{v} \\ \mathbf{a} - \mathbf{Ad}(\omega) \cdot \mathbf{v} \\ \omega \end{pmatrix}$$

$$\mathbf{u} = (a_x, a_y, \omega)^{\mathrm{T}}$$

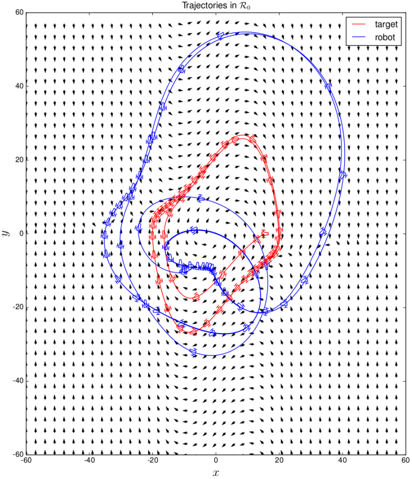
Simple attractive field

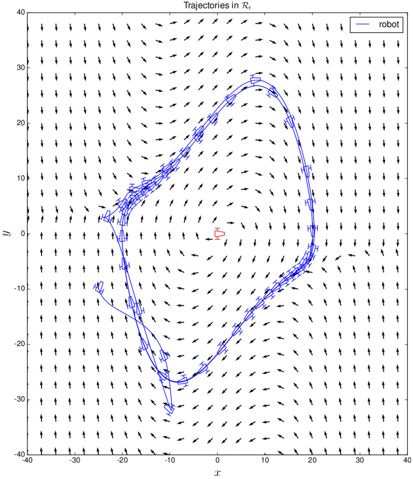
$$\boldsymbol{\Psi}\left(\mathbf{p}_{r,\mathcal{R}_t}\right)_{\mathcal{R}_t} = -\mathbf{p}_{r,\mathcal{R}_t}$$



Van der Pol cycle

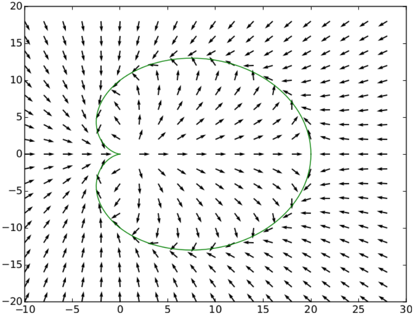
$$\mathbf{\Psi}(x,y)_{\mathcal{R}_t} = \begin{pmatrix} y \\ -(0.01x^2-1)\,y-x \end{pmatrix}$$



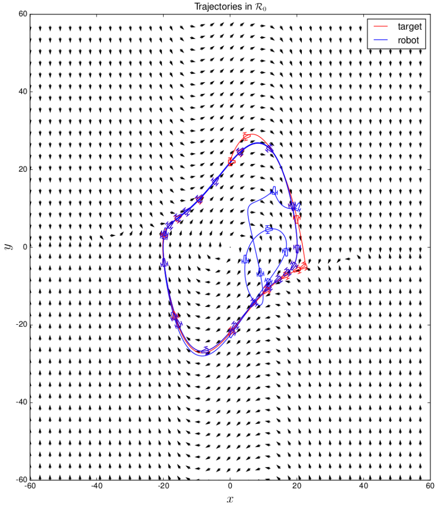


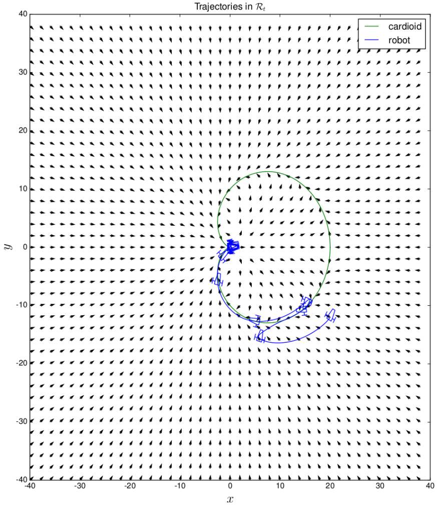
Cardioid vector field I

$$\theta = \arctan2\left(\mathbf{p}_{r,y}, \mathbf{p}_{r,x}\right)$$
$$t_x\left(\theta\right) = -R\left(\sin\left(2\theta\right) + \sin\left(\theta\right)\right)$$
$$t_y\left(\theta\right) = R\left(\cos\left(2\theta\right) + \cos\left(\theta\right)\right)$$
$$r\left(\theta\right) = R\left(1 + \cos\left(\theta\right)\right)$$
$$\mathbf{\Psi}\left(\mathbf{p}_{r,\mathcal{R}_t}\right)_{\mathcal{R}_t} = \mathrm{sign}\left(\theta\right)\begin{pmatrix} t_x \\ t_y \end{pmatrix} - \left(\|\mathbf{p}_r\| - r\left(\theta\right)\right)\mathbf{p}_r$$



Cardioid vector field II





Conclusion

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- Promising method for docking problems :
  - Improved robustness w.r.t. environment's disturbances
  - No overshoot phenomenon
  - Anticipates the target's moves
  - Mathematically simple to derive and implement
  - Drives the robot along a given vector field, which can be tuned to suit every need
- Limitations :
  - Requires generally a vector field of class $\mathcal{C}^2$, sometimes more
  - A state model of the robot is required
  - The position/orientation, linear/angular velocities and accelerations of the target must be known
  - Finding a suitable vector field can be a bit tricky

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Future research

- Find an elegant expression for a docking vector field
- Develop a method based on Interval Analysis to validate the vector field w.r.t. hardware limitations

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References

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