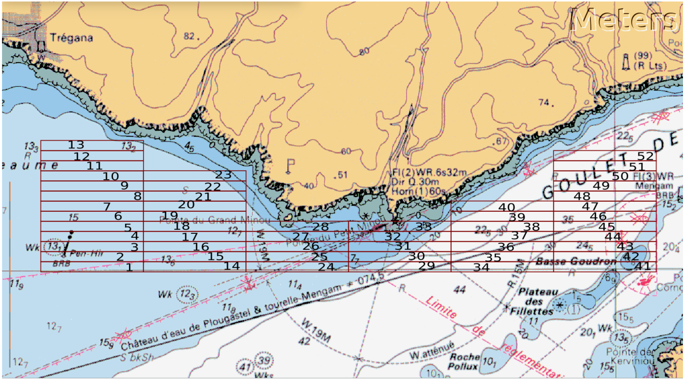
Ocean exploration with underwater robots

L. Jaulin

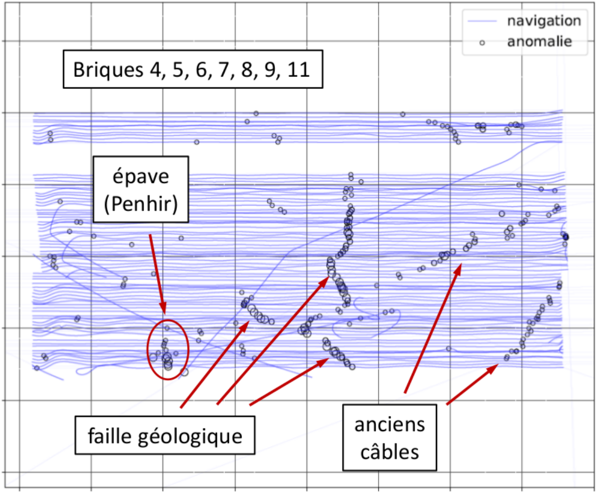
MOQESM'2020
Sea-Tech-Week, October 15, 2020

1. Marine robots to build maps


Meters
Trégana
GOULET DE
Pointe du Grand Minou
Fl(2)WR.6s32m
Dir Q.30m
Horn(1)60s
Château d'eau de Plougastel & tourelle Mengam
Plateau des Fillettes
Basse Goudron
Roche Pollux
W.atténué
Pen-Hir

Boatbot tows a magnetometer

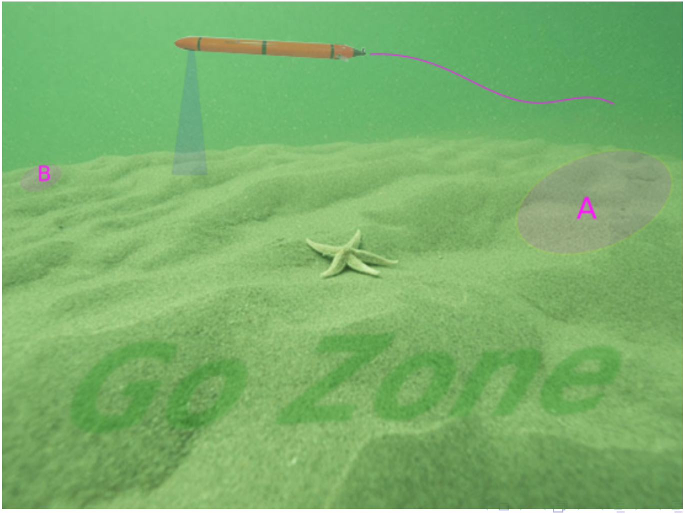
youtu.be/cxVs1fDdm1s

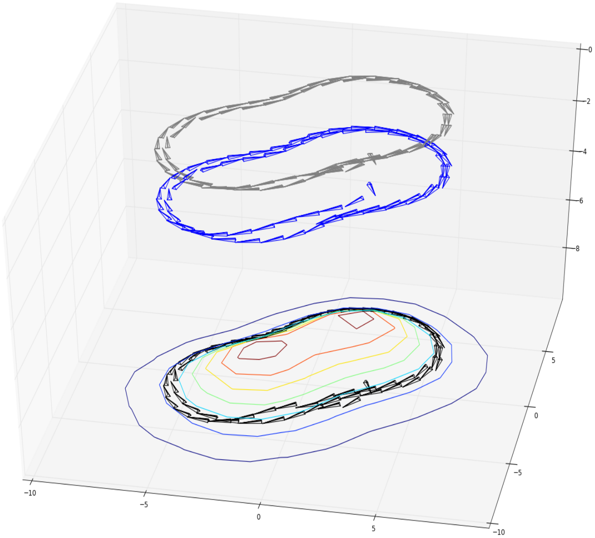


Magnetic map built in 2018

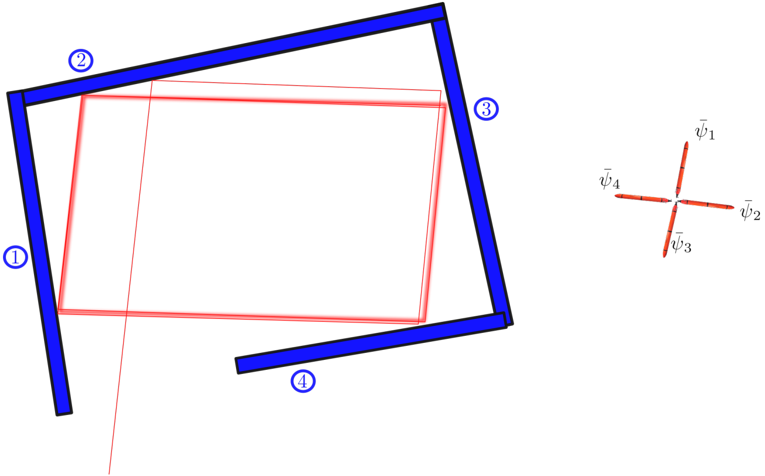
2. Cycles

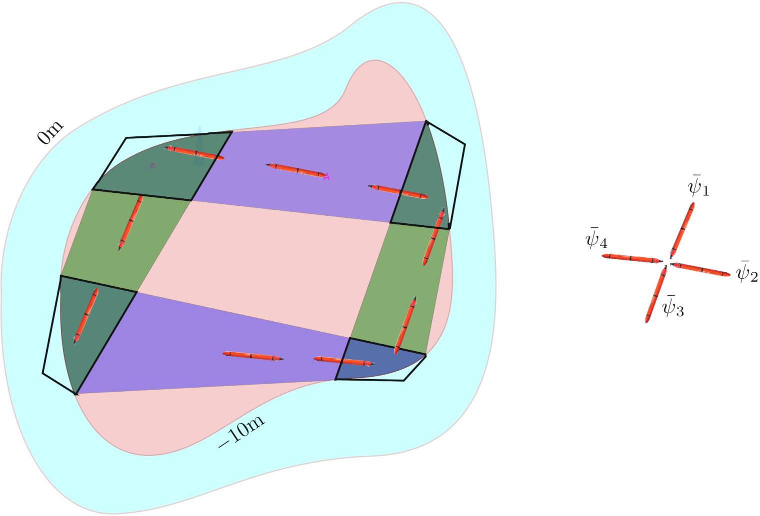
Submeeting 2018

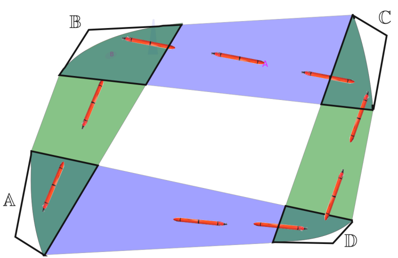

B
A
Go Zone

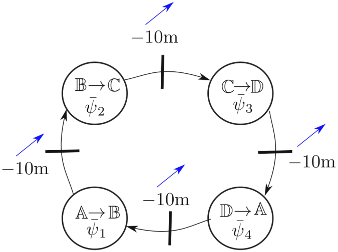


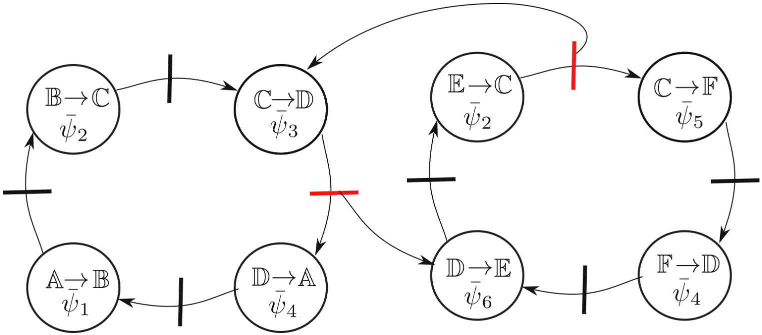
[3]


②
③
①
④
$\bar{\psi}_1$
$\bar{\psi}_4$
$\bar{\psi}_2$
$\bar{\psi}_3$


0m
−10m
A
$\bar{\psi}_1$
$\bar{\psi}_2$
$\bar{\psi}_3$
$\bar{\psi}_4$


B
C
A
D


−10m
B→C
$\bar{\psi}_2$
C→D
$\bar{\psi}_3$
−10m
−10m
−10m
A→B
$\bar{\psi}_1$
D→A
$\bar{\psi}_4$


$\mathbb{B} \to \mathbb{C}$ $\bar{\psi}_2$
$\mathbb{C} \to \mathbb{D}$ $\bar{\psi}_3$
$\mathbb{E} \to \mathbb{C}$ $\bar{\psi}_2$
$\mathbb{C} \to \mathbb{F}$ $\bar{\psi}_5$
$\mathbb{A} \to \mathbb{B}$ $\bar{\psi}_1$
$\mathbb{D} \to \mathbb{A}$ $\bar{\psi}_4$
$\mathbb{D} \to \mathbb{E}$ $\bar{\psi}_6$
$\mathbb{F} \to \mathbb{D}$ $\bar{\psi}_4$

3. Mapping

For *topological navigation*, the robot may follow paths. A path can correspond
1) to an isothermal front
2) to a magnetic path
3) to a parallel
4) to an isobath.

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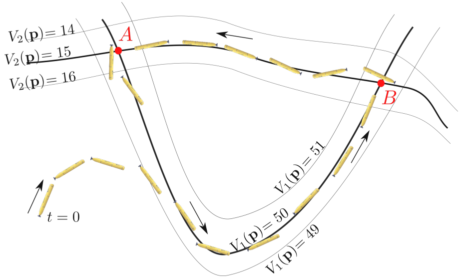
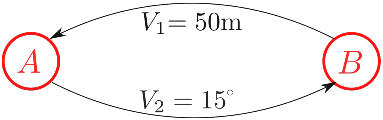
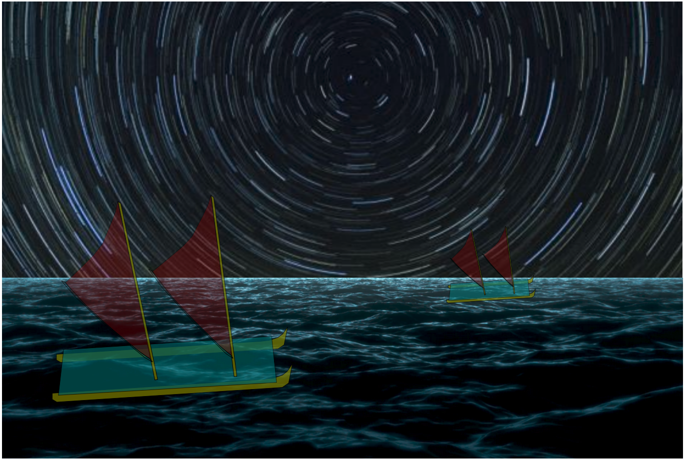


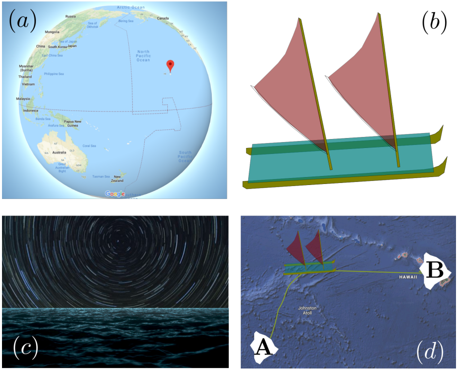
1. Follow the 50m isobath until the 15-degree isotherm
2. Follow the 15-isotherm until the 50m isobath
3. Go to Step 1

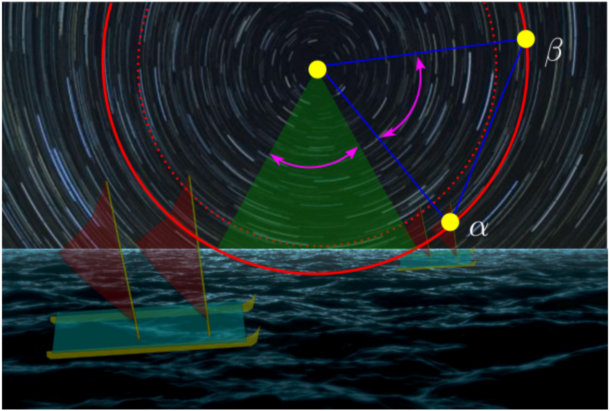

$V_1 = 50\text{m}$
A
B
$V_2 = 15^\circ$

4. Exploration



Find the route without GPS, compass and clock


(a)
(b)
(c)
(d)
B
HAWAII
Johnston
Atoll
A


β
α

Formalization

Given

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{f}(\mathbf{x},\mathbf{u}), & \mathbf{u}(t) \in [\mathbf{u}](t) \\ \mathbf{y} = \mathbf{g}(\mathbf{x}), & \mathbf{y}(t) \in [\mathbf{y}](t) \\ \mathbf{x}(0) = \mathbf{x}_0 \end{cases}$$

An observer is *blind* if dim$\mathbf{y}= 0$.

Visible area. The robot has a state $\mathbf{x}$. The visible area is $\mathbb{V}(\mathbf{x})$
Example. The robot is able to see all up to 3 km:

$$\mathbb{V}(\mathbf{x}) = \left\{ (z_1, z_2) \,|\, \sqrt{(z_1 - x_1)^2 + (z_2 - x_2)^2} \leq 3 \cdot 10^3 \right\}.$$

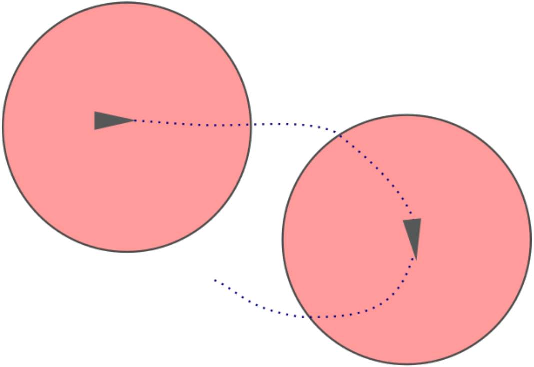
Explored zone $\mathbb{Z}$ is defined by [1]

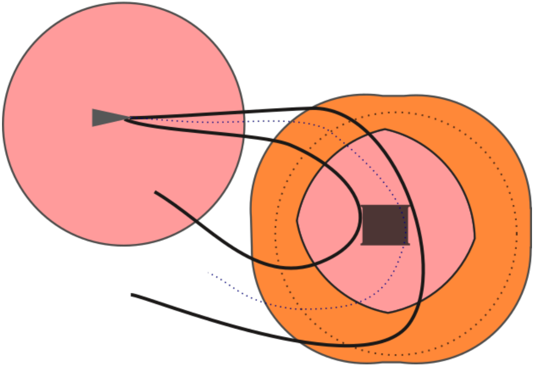
$$\begin{cases} \dot{\mathbf{x}} = \mathbf{f}(\mathbf{x},\mathbf{u}),\ \mathbf{u}(t) \in [\mathbf{u}](t) \\ \mathbb{Z} = \bigcup_{t \geq 0} \mathbb{V}(\mathbf{x}(t)) \\ \mathbf{x}(0) = \mathbf{x}_0 \end{cases}$$

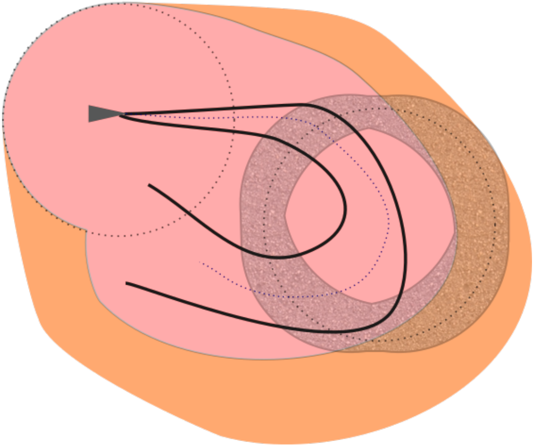
We have

$$\underbrace{\bigcap_{\mathbf{x}(\cdot)\in\mathscr{X}(\cdot)} \bigcup_{t\geq 0} \mathbb{V}(\mathbf{x}(t))}_{\mathbb{Z}^-} \subset \mathbb{Z} \subset \underbrace{\bigcup_{\mathbf{x}(\cdot)\in\mathscr{X}(\cdot)} \bigcup_{t\geq 0} \mathbb{V}(\mathbf{x}(t))}_{\mathbb{Z}^+}.$$

$\mathbb{Z}^-$ is the *certainly explored zone.*
$\mathbb{Z}^+$ is the *maybe explored zone*.
$\mathbb{Z}^+ \backslash \mathbb{Z}^-$ is the *penumbra.*

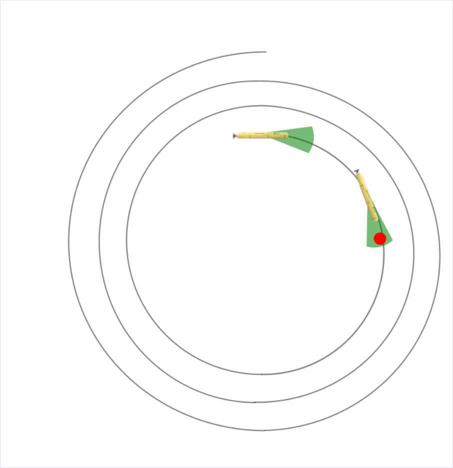


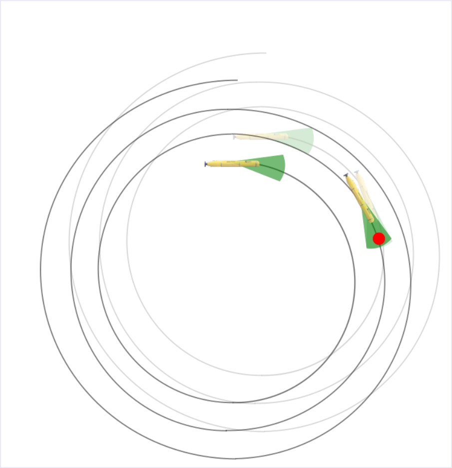


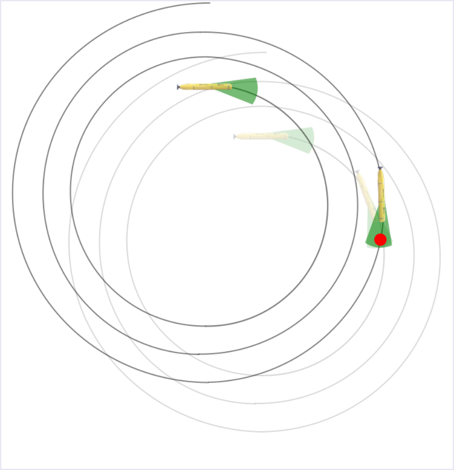


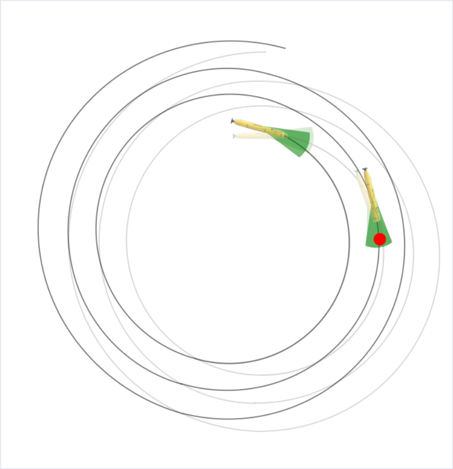
Spiral scan. We have [2]

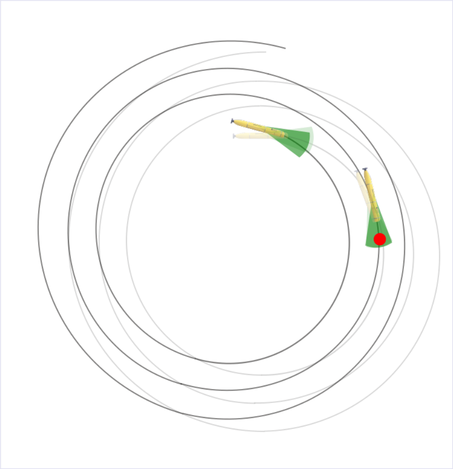
$$\underbrace{\bigcup_{t\geq 0}\ \bigcap_{\mathbf{x}\in\mathscr{X}(t)} \mathbb{V}(\mathbf{x})}_{\{\mathbf{z}\ \mid\ \exists t\ \forall \mathbf{x}\in\mathscr{X}(t),\ \mathbf{z}\in\mathbb{V}(\mathbf{x})\}} \subset \mathbb{Z}^{-} = \underbrace{\bigcap_{\mathbf{x}(\cdot)\in\mathscr{X}(\cdot)}\ \bigcup_{t\geq 0} \mathbb{V}(\mathbf{x}(t))}_{\{\mathbf{z}\ \mid\ \forall \mathbf{x}(\cdot)\in\mathscr{X}(\cdot),\exists t,\ \mathbf{z}\in\mathbb{V}(\mathbf{x})\}}$$

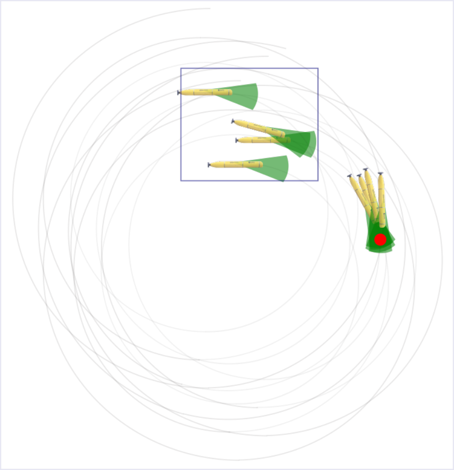




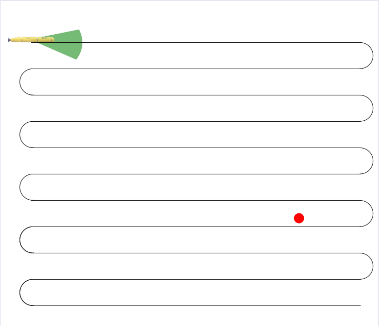


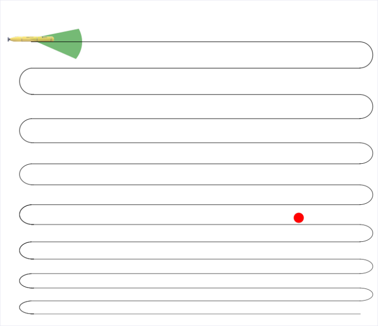


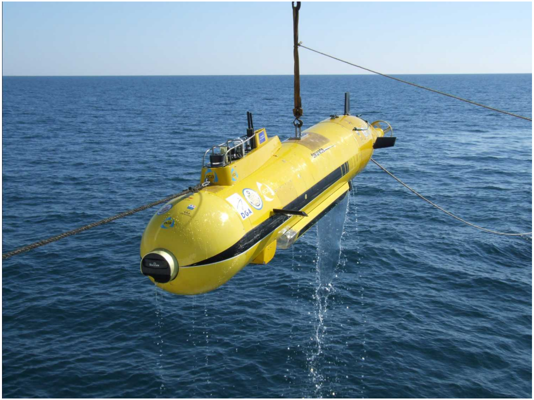




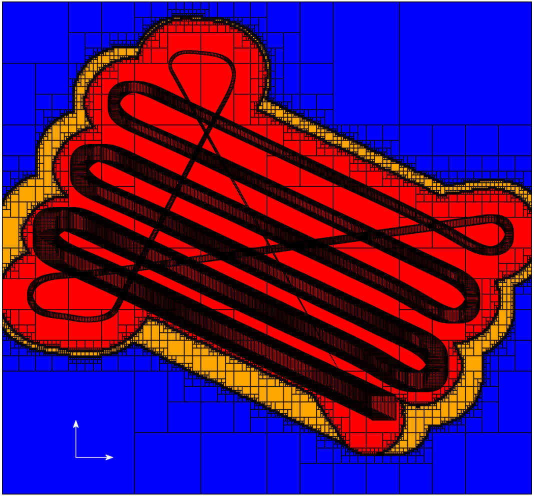
Boustrophedon







Daurade DGA-TN



During its boustrophedon Daurade explored $\mathbb{Z} \in [[\mathbb{Z}]]$

B. Desrochers and L. Jaulin.
Computing a guaranteed approximation the zone explored by a robot.
IEEE Transaction on Automatic Control, 62(1):425–430, 2017.

V. Drevelle, L. Jaulin, and B. Zerr.
Guaranteed characterization of the explored space of a mobile robot by using subpavings.
In *Proc. Symp. Nonlinear Control Systems (NOLCOS'13)*, Toulouse, 2013.

L. Jaulin.
Isobath Following using an Altimeter as a Unique Exteroceptive Sensor.
In Sophia M. Schillai and Nicholas Townsend, editors, *Robotic Sailing 2018*, pages 105–110, 2018.