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Periodic Trajectories of Mobile Robots

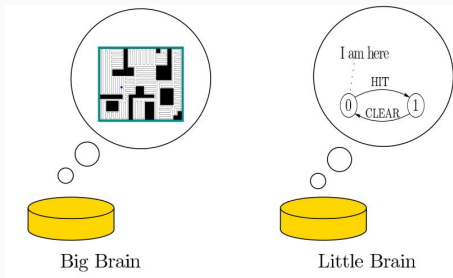
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Simple Mobile Robots

- Mobile robots can vacuum floors, transport goods in warehouses, act as security robots (patrol), etc
- We want to **minimize** sensing and computation (less expensive, more energy efficient)
- Often, they can bump into things and be ok!
- How can we use **contact with the environment** as a strategy or source of information?



Blind, Bouncing Robots¹

Abstract the robot as a point moving in the plane, “bouncing” off the boundary at a fixed angle θ from the normal:

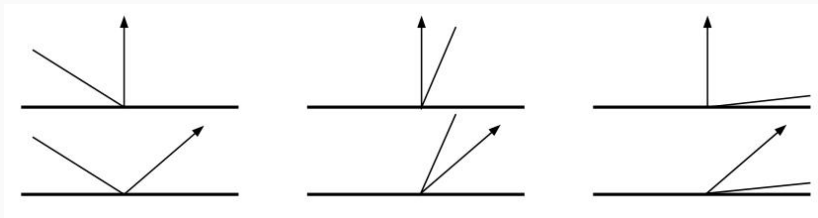


Figure 1: A point robot moving in the plane. The top row shows bounces at zero degrees from the normal. The second row shows bounces at 50 degrees clockwise from normal.

¹(Erickson and LaValle 2013), ICRA

Research Questions

Given a constant control strategy, will the robot become “trapped” in part of the environment? Or in a certain motion pattern? We focus on **patrolling**: periodically orbiting the workspace.

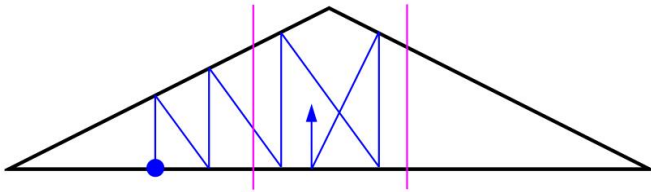


Figure 2: In this environment, bouncing at the normal, the robot will become trapped in the area between the purple lines

Ok, but why?

- Using geometry of a space, can create movement strategies with guaranteed properties (here, following a periodic path)
 - warehouses, offices, need patrolling robots to monitor conditions
 - what is the minimal sensing/computation/actuation required?
- Assume robot has two primitives
 - move straight
 - align heading wrt wall normal

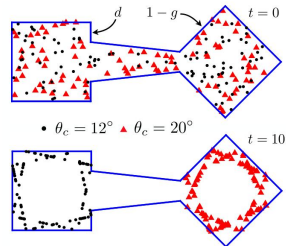
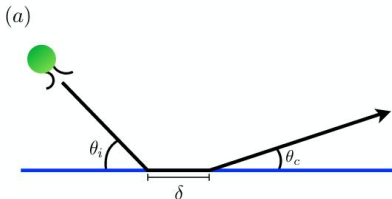
But is it physically realizable?

- can implement on a roomba with bump sensor and IR prox detector²
- “collisions” can be virtual - for example, robot stops when it is collinear with two landmarks, and rotates until one landmark is at a certain heading

²(Lewis and O’Kane 2013), IJRR

Related Work

- minimal sensing, actuation, computation requirements for mapping, navigating, localizing, patrolling, pursuit evasion (*Tovar, Guilamo, and LaValle (2005), Bilò et al. (2012), J. M. O'Kane and LaValle (2007), Disser (2011)*)
- specular billiards (*Tabachnikov (2005)*), pinball billiards (*Markarian, Pujals, and Sambarino (2010)*)
- **aspecular billiards**, microorganism billiards (*Spagnolie et al. (2017)*)



Limit Cycles In Regular Polygons

Question

If we can only move in straight lines and align relative to wall normal:

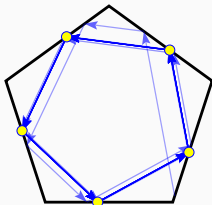
*Can we guarantee that a robot **patrols** a space on a periodic path?*

Can also phrase as:

What are the conditions on limit cycles in this dynamical system?

Discovery Through Simulation

- Haskell with *Diagrams* library (Yorgey 2012)
- fixed-angle bouncing, relative bouncing (rotate θ from previous heading), specular bouncing, add noise
- render diagrams from simulations automatically³



³<https://github.com/alexandroid000/bounce>

In Regular Polygons

Ignore movement in interior, only track position on boundary when robot collides. Defines a **discrete dynamical system**

$$x_{n+1} = f(x_n)$$

Given regular polygon, with edge length ℓ and internal angle ϕ , we can define the mapping function

$$b_\theta : (0, \ell) \rightarrow (0, \ell)$$

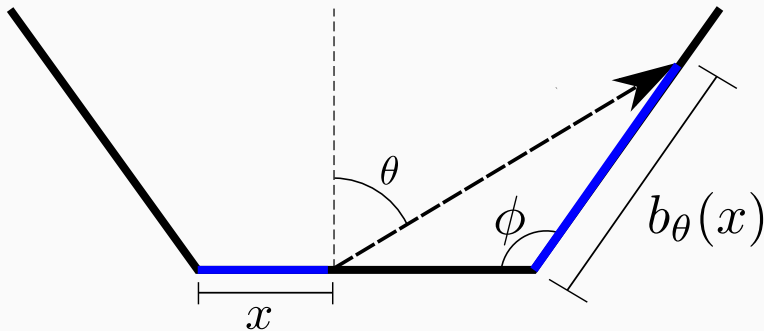
Sequential-Edge Bouncing

In regular polygons with side length ℓ and internal angle ϕ :

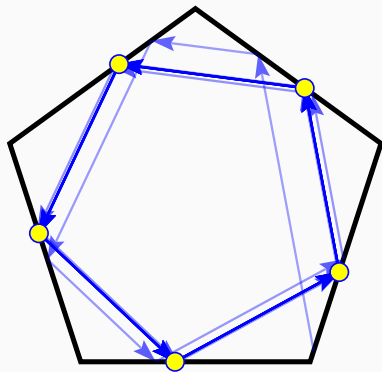
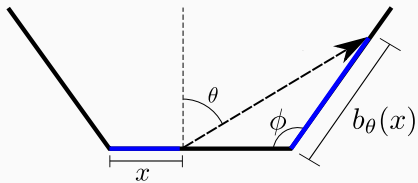
$$b_\theta : (0, \ell) \rightarrow (0, \ell)$$

$$b_\theta(x) = c(\theta)(\ell - x)$$

$$c(\theta) = \frac{\cos(\theta)}{\cos(\theta - \phi)}$$



Fixed Point of Mapping Function \iff Periodic Orbit

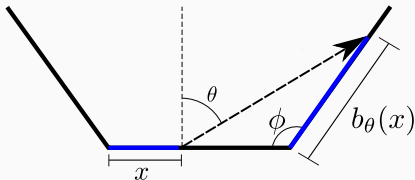


What is the Fixed Point?

Mapping Function

$$b_{\theta}(x) = c(\theta)(\ell - x)$$

$$c(\theta) = \frac{\cos(\theta)}{\cos(\theta - \phi)}$$



$$b_{\theta}(x_{FP}) = x_{FP}$$

$$c(\theta)(\ell - x_{FP}) = x_{FP}$$

$$x_{FP} = \frac{\ell c(\theta)}{1 + c(\theta)}$$

For clockwise bouncing, reflect across the midpoint of the edge:

$$\rightarrow \ell - x_{FP}$$

Is the Fixed Point Unique?

Mapping Function

$$b_{\theta}(x) = c(\theta)(\ell - x) \qquad c(\theta) = \frac{\cos(\theta)}{\cos(\theta - \phi)}$$

When we check how distances change under the map, we see that

$$\begin{aligned} d(b_{\theta}(x), b_{\theta}(y)) &= |c(\theta)(\ell - y) - c(\theta)(\ell - x)| \\ &= |c(\theta)(x - y)| \\ &= |c(\theta)|d(x, y). \end{aligned}$$

Thus if $|c(\theta)| < 1$, then b_{θ} is a contraction mapping, and by the Banach fixed-point theorem, it has a unique fixed point (Granas and Dugundji 2003).

Bounds on θ

To get bounds on θ for guaranteeing periodic trajectories:

- solve $|\frac{\cos(\theta)}{\cos(\theta-\phi)}| < 1$
- take geometric feasibility into account (for non-regular polygons)

So now we have a statement for the existence and stability of the fixed points, for counterclockwise bouncing striking each edge of a regular polygon:

Proposition

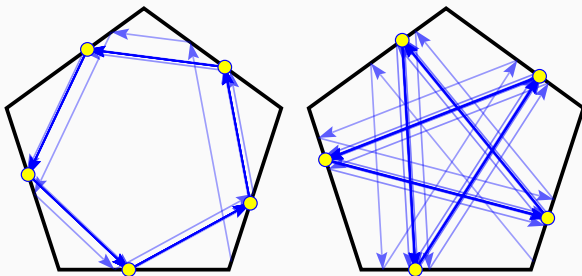
$$x_{FP} = \begin{cases} \frac{\ell c(\theta)}{1+c(\theta)} & \phi/2 < \theta < \pi/2 \\ \frac{\ell}{1+c(\theta)} & -\pi/2 < \theta < -\phi/2 \end{cases}$$

in which $c(\theta) = \cos(\theta)/\cos(\theta - \phi)$.

Confirmation and Generalization

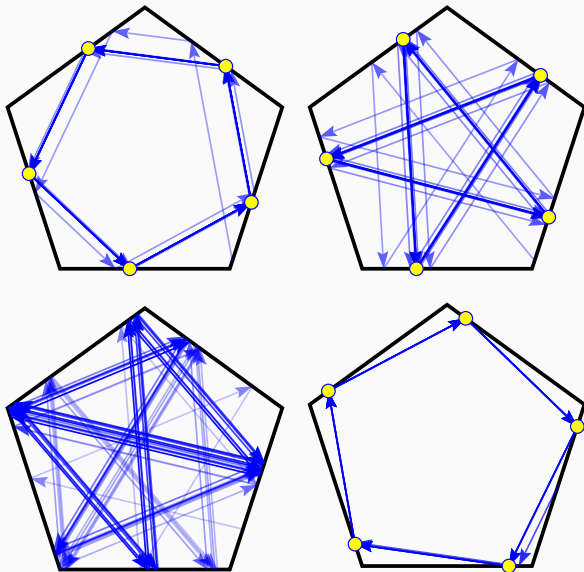
We have shown the case for counterclockwise bounces, on every sequential edge.

We can also imagine going clockwise, and/or skipping edges:



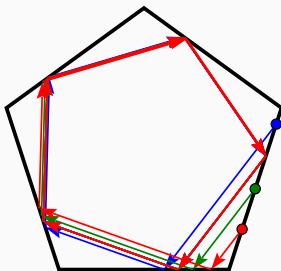
Mapping function, convergence conditions go through very similarly (see paper)

Simulation Results



Nice Properties

- any regular n -gon
- stable orbits are **independent of starting position**
- exponential convergence
- bounds on θ from $|c(\theta)| < 1$: any angle in this range will make similar orbits



Adding Noise

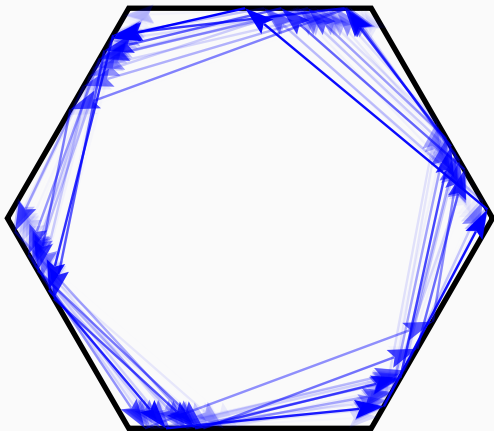
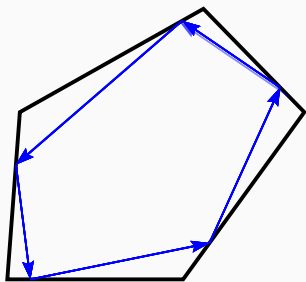
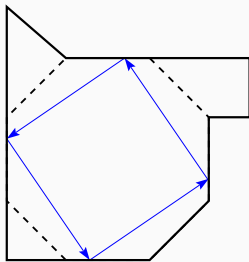


Figure 5: 200 bounces with uniformly distributed error added to θ , $-0.1 \text{ rad} \leq \epsilon \leq 0.1 \text{ rad}$

Other Polygons



(a) A stable orbit in a sheared pentagon.

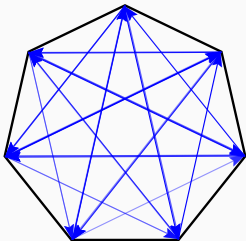


(b) A stable orbit in a nonconvex environment.

Figure 6: Stable orbits also exist in non-regular polygons.

Open Problems & Future Work

- How to characterize and exploit non-periodic dynamics?
 - Lyapunov exponents suggest chaotic dynamics
 - relationship to dispersion: what is the longest unvisited edge interval as the system evolves?
- Extensions to non-regular polygons and smooth environments
- Error bounds: model different disturbances to bounce
- Feedback control: counting number of bounces, make walls distinguishable / colored, allow robot to place and/or detect landmarks



Thank you!

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