Distributed Algorithms for Large-scale Robotic Ensembles: Centrality, Synchronization and Self-reconfiguration

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Thesis Defense

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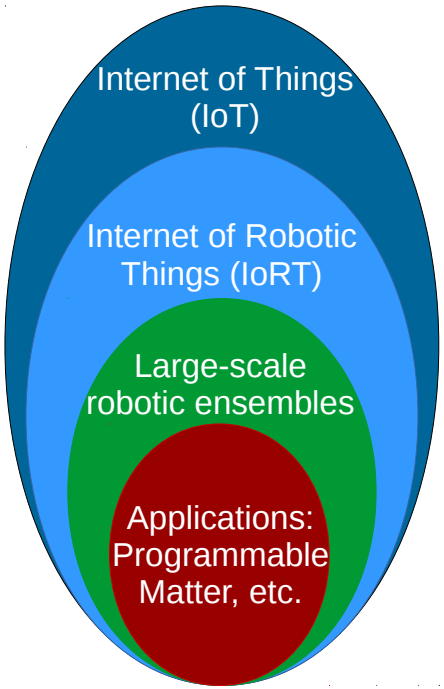
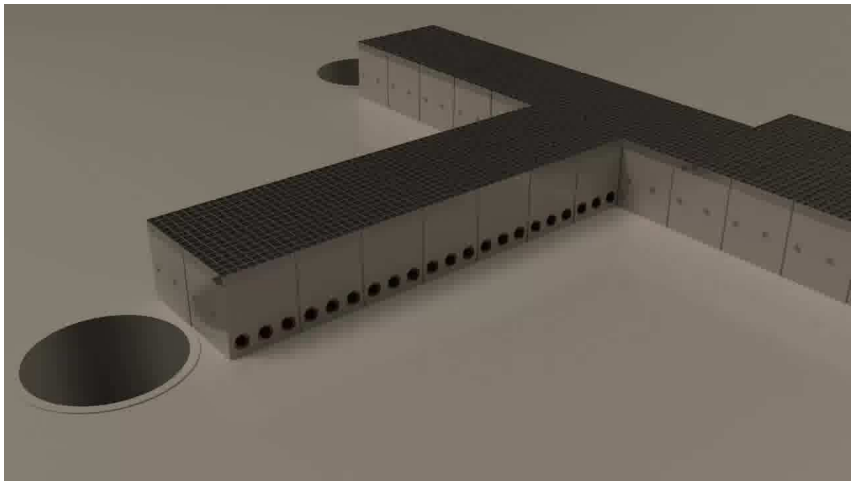
(contracts ANR-12-IS02-0004-01
and 3-ZG1F)

Outline

Large-scale Robotic Ensembles



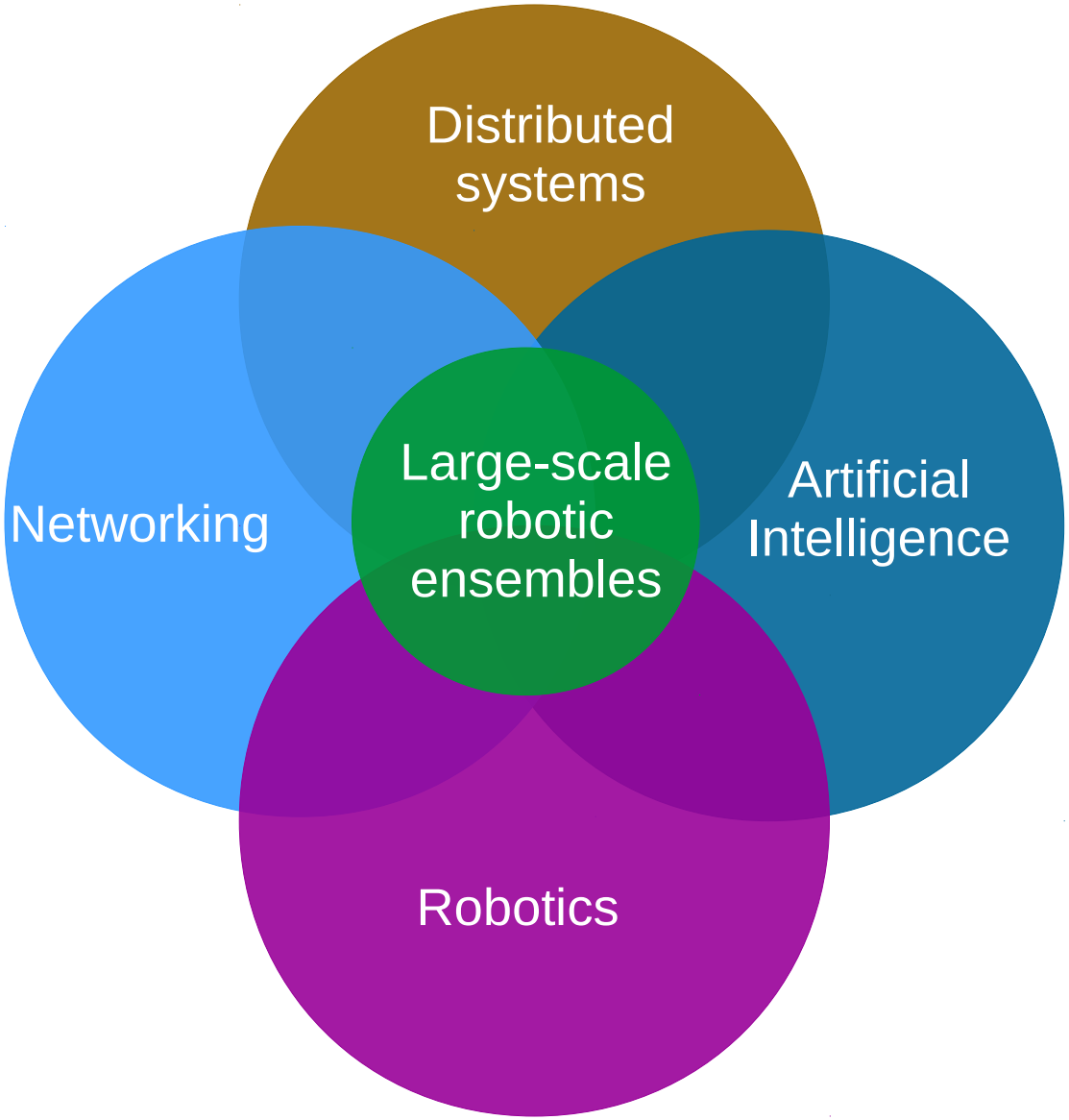
- Modular robotics, swarm robotics, distributed MEMS, robotic materials
- Macro-scale: reconfigurable IoRT objects
- Micro-scale: self-organized ensembles
  - up to 10^6 units
  - small and resource-constrained (energy, memory, computation) units
- Advantages: versatility, robustness, cheaper



Conveying Surface
Smart Blocks project (FEMTO-ST)

Programmable Matter
Claytronics project (CMU)

An Inter-Disciplinary Domain



Challenges:

- Hardware: Fabrication
- Algorithmic: Distributed coordination

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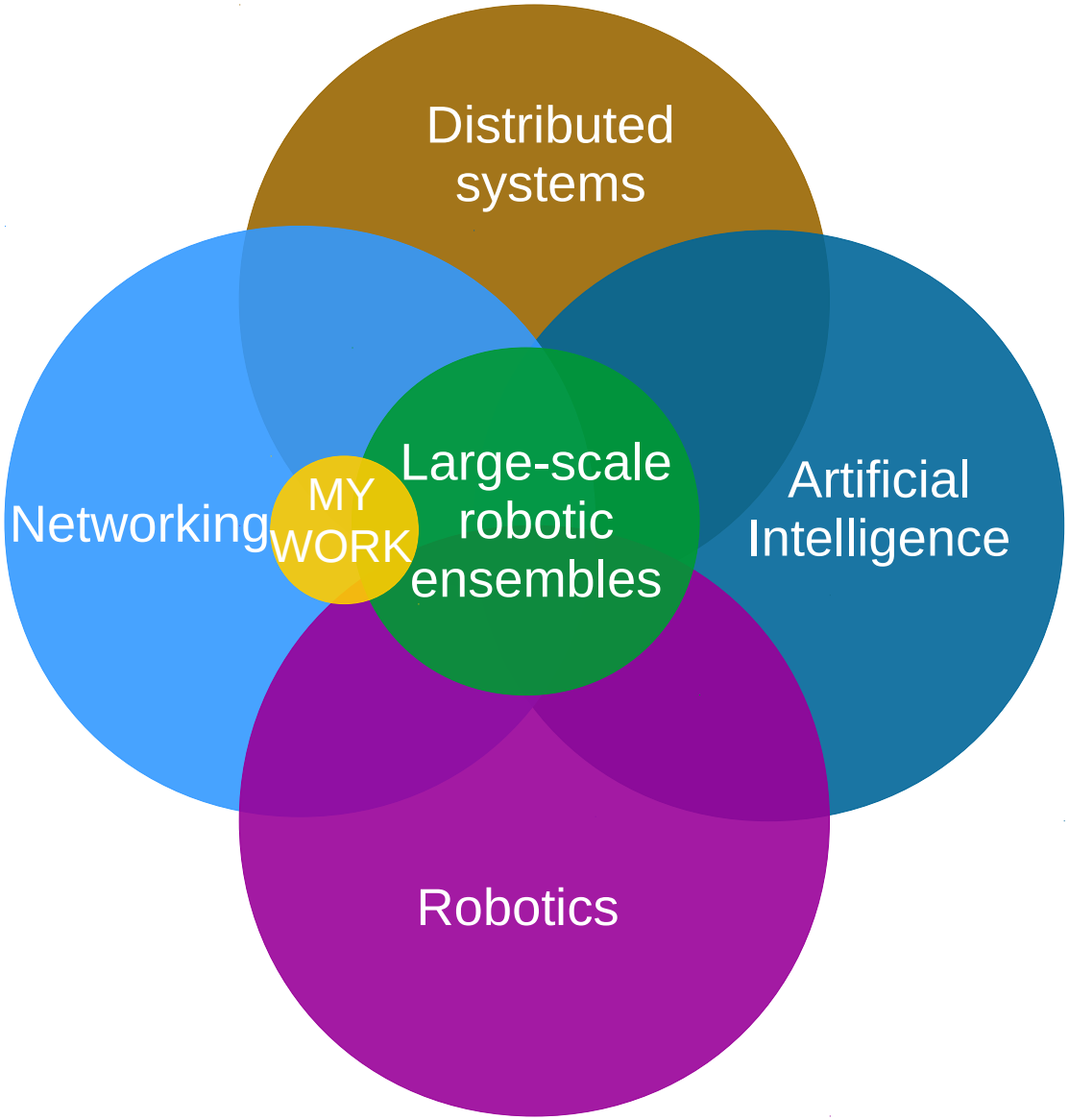

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my work

Problem Statement

- Coordination of large-scale ensembles of resource-constrained robots
  $\Longrightarrow$ New algorithmic challenges
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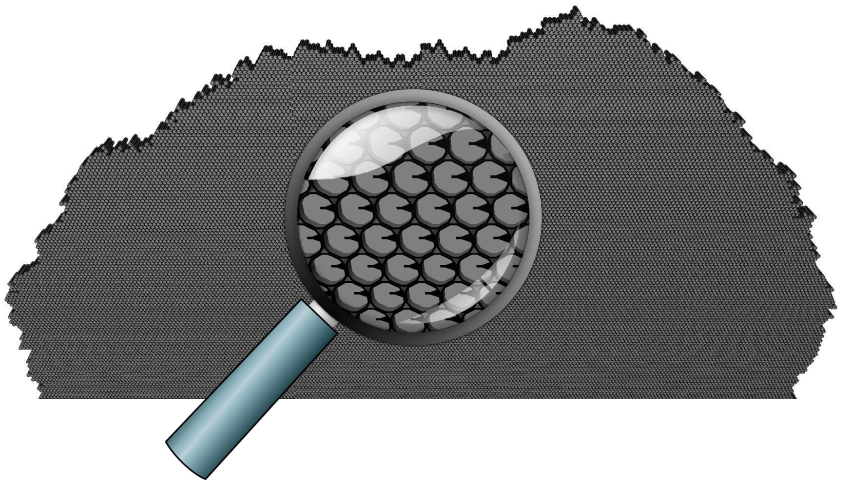

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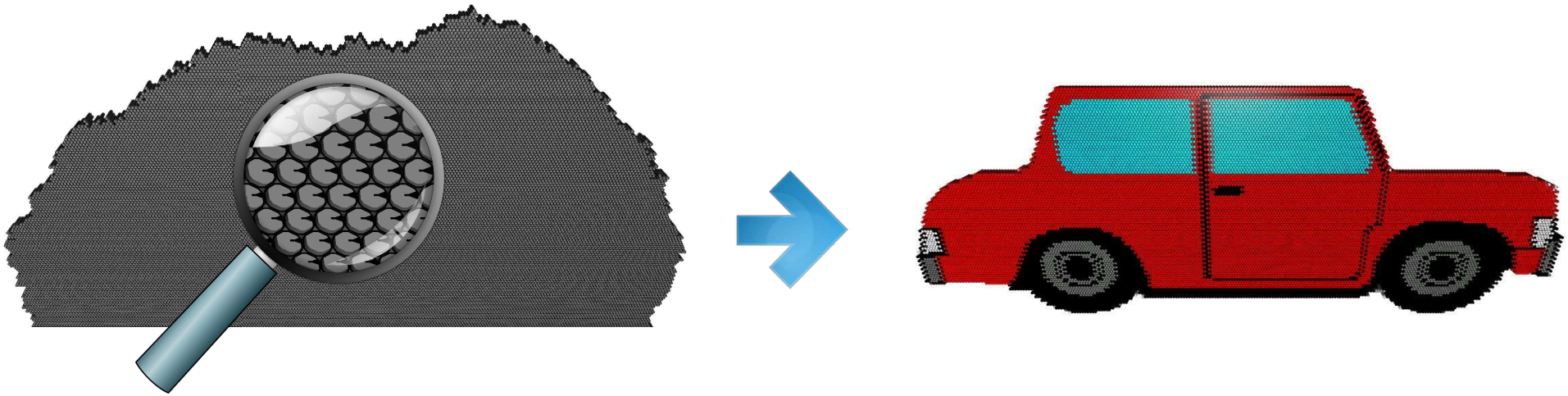

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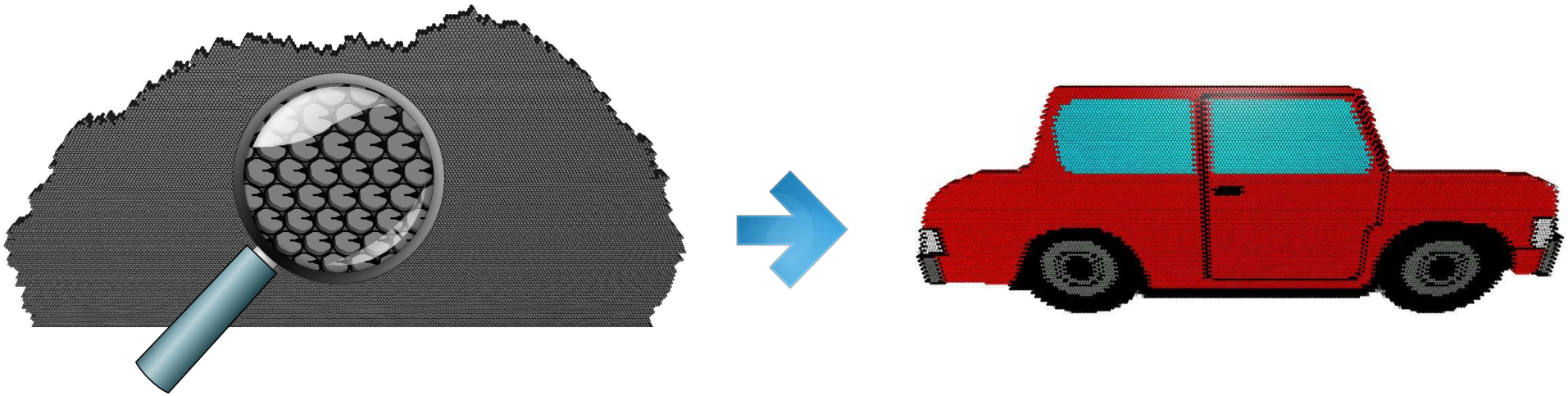

- Research problems (proposed high-level primitives):
  1. Shape construction
  2. Time synchronization
  3. Centrality-based leader election

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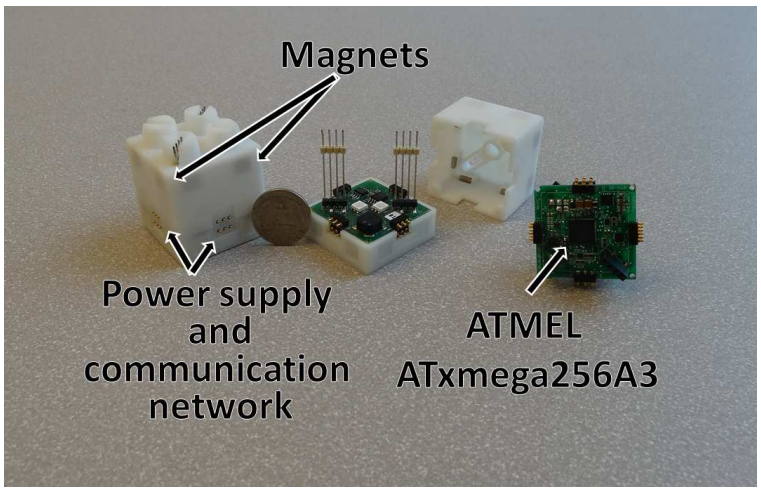
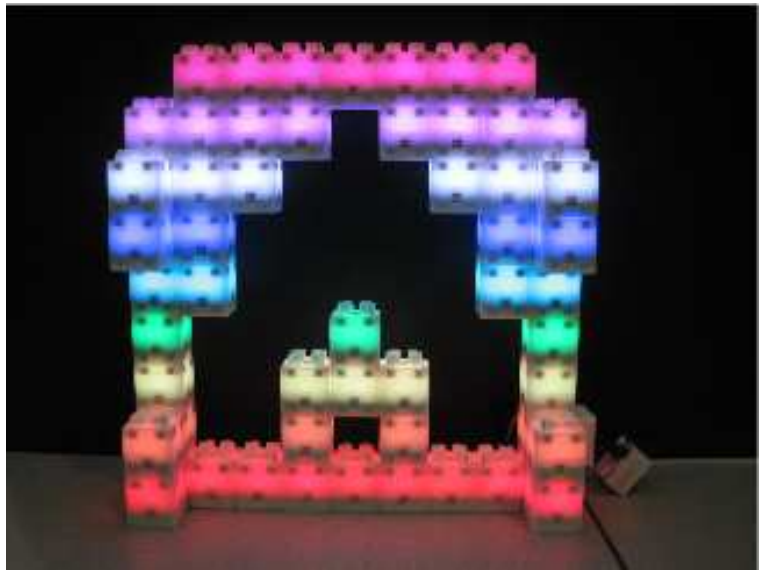
Section Outline

The Blinky Blocks

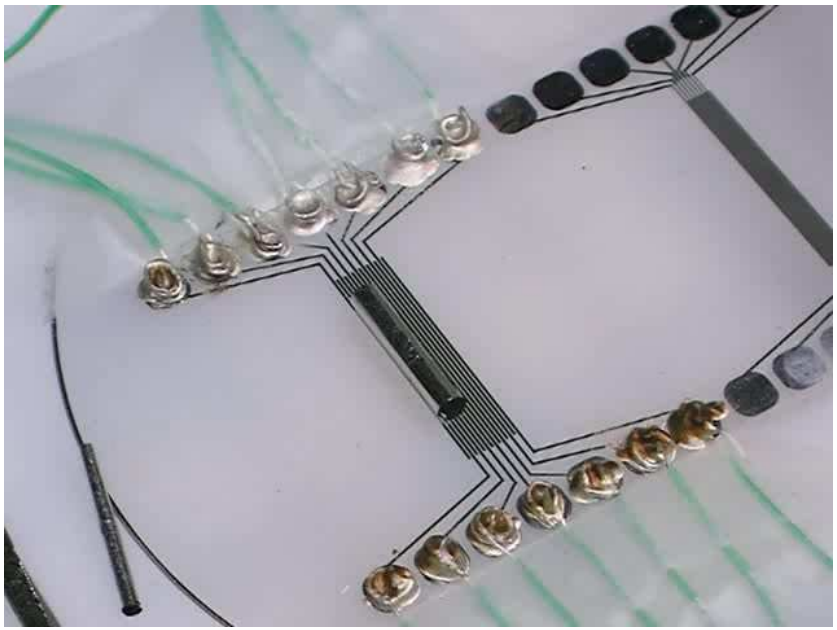
- Several generations:
  - Originally developed at Carnegie Mellon University [Kirby et al., 2011]
  - Last generations fabricated by FEMTO-ST
- Hardware features
  - micro-controller: ATMEL ATxmega256A3-AU 8/16-bits 32MHz
  - memory: 256KB ROM and 16KB RAM
  - Network: 6 serial interfaces configured at 38.4 kbit/s
  - RGB leds
  - Local Clock: Real-Time Counter driven by a RC oscillator
    - 1% accuracy and 1ms resolution



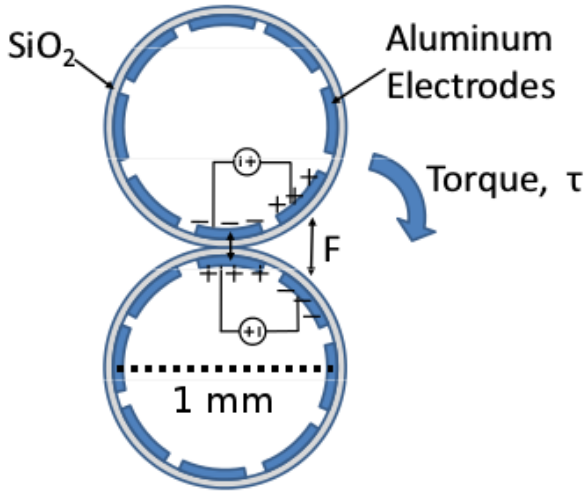


The 2D Catoms

Partially validated 2D Catom hardware prototype [Karagozler et al., 2009]



Hardware prototype



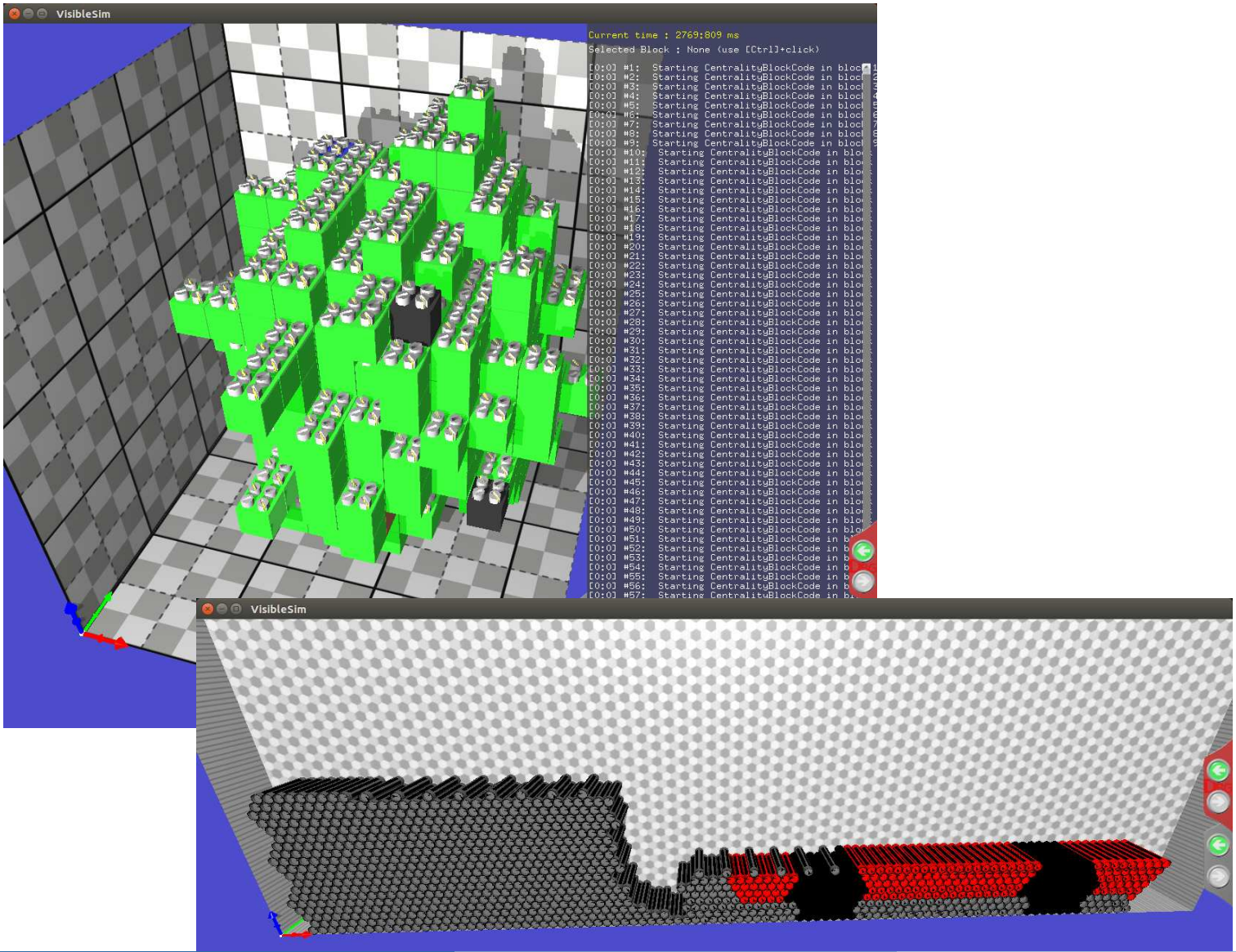
Actuation scheme

Partially validated:

- Only motion on the ground
- No communication, nor module arrangement, nor color for now

VisibleSim

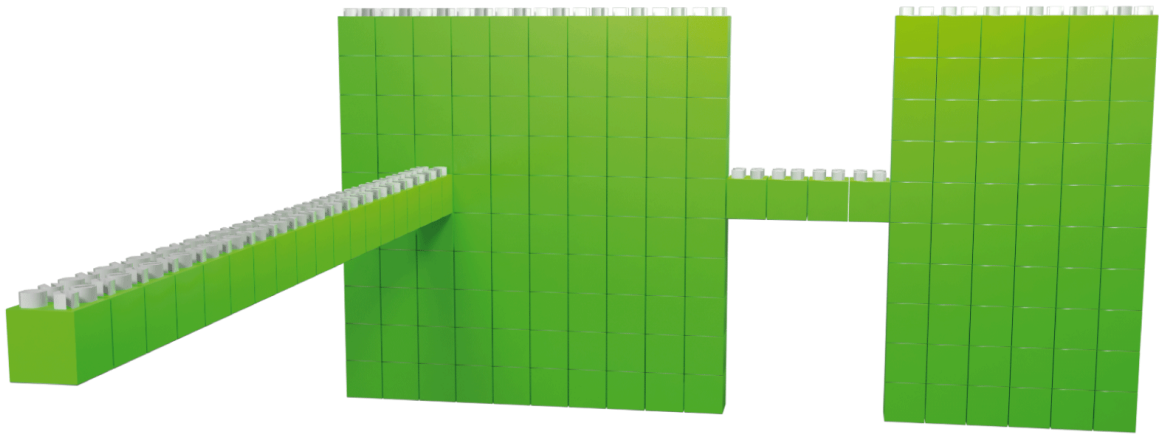
Simulator of modular robotic ensembles [Dhoutaut et al., 2013]



Section Outline

Problem and Motivations

- Network graph G(V,E): V = modules, E = connections
  - Neighbor-to-Neighbor communications, unique node identifiers
  - $d(v_i, v_j)$ = hop distance between modules v_i and v_j



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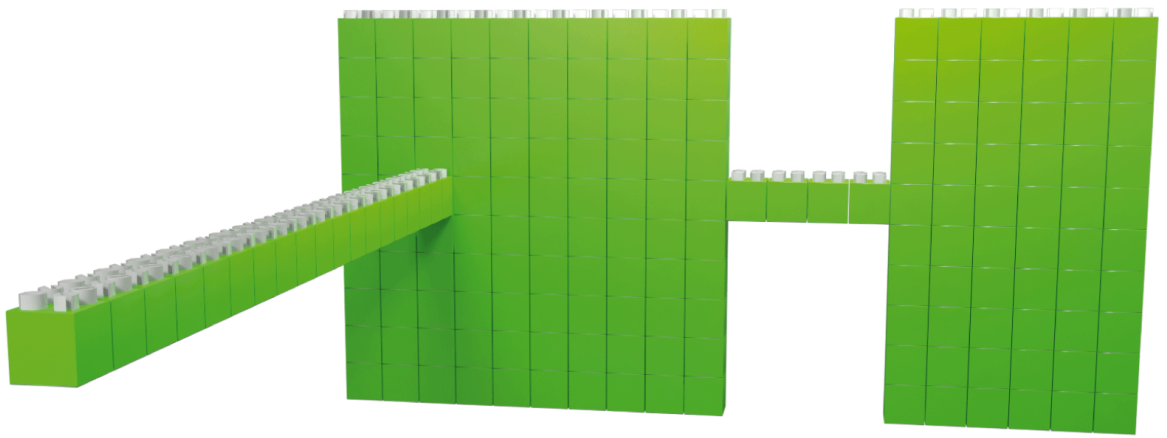

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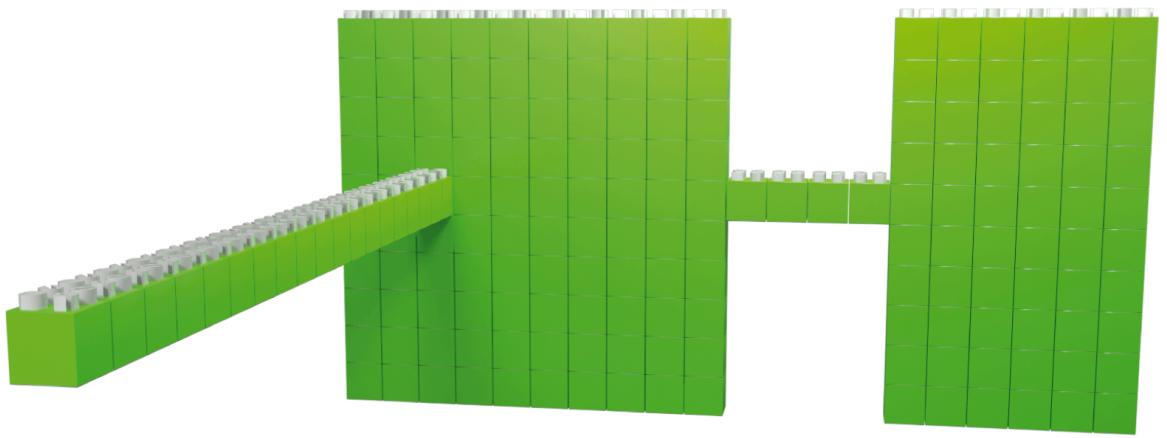

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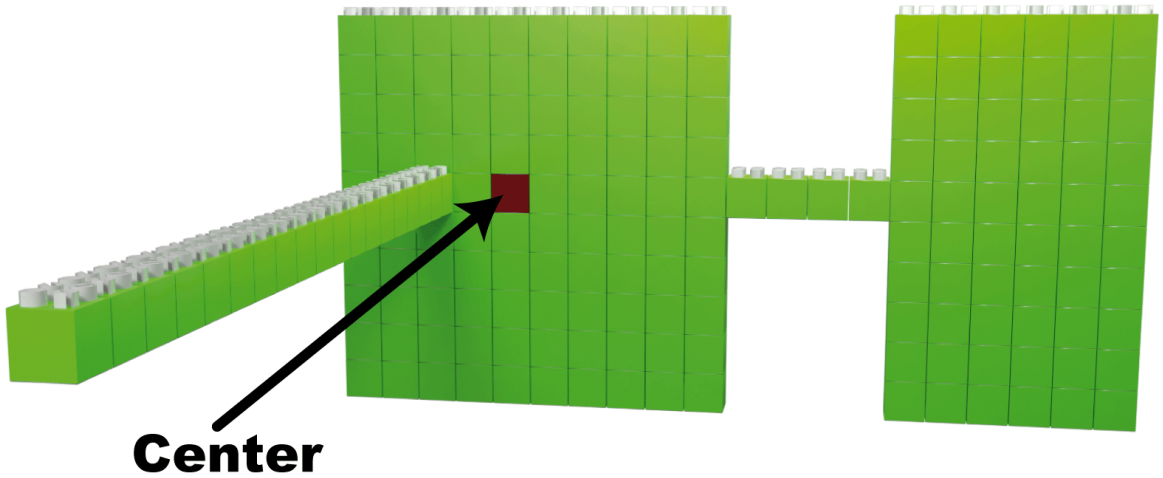
  - Center: minimizes the maximum distance to all the others

$$Center = \underset{v_i \in V}{\operatorname{argmin}}\, ecc(v_i) = \underset{v_i \in V}{\operatorname{argmin}} \max_{v_j \in V} d(v_i, v_j)$$



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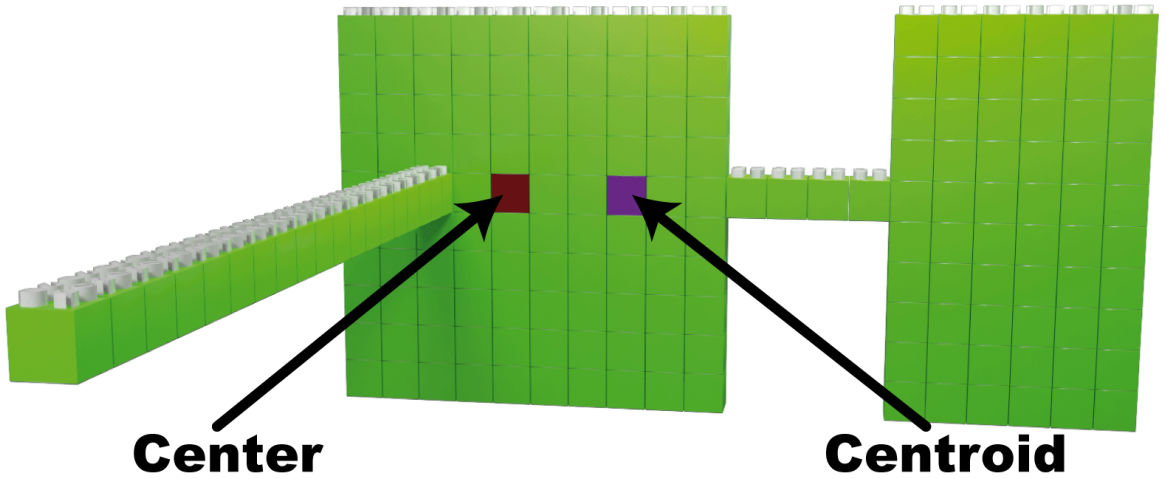

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- Challenge: requires a distributed all-pair shortest path computation
  - Large time, message and/or storage costs.
- Motivation: ideal nodes for communications with all the others
  - Example: service providers
    - Time synchronization: the precision decreases with the hop distance to the time master

Subsection Outline

Related Work

Approach	Accuracy (experiments)	Time and message cost	Memory cost
Naive and exhaustive (e.g., [Korach et al., 1984, Mamei et al., 2005])	exact	+++++ (potential congestion)	+ to +++++
Graph specific (e.g., [Bruell et al., 1999] for trees)	exact (but not for arbitrary graphs)	+	+
Approximation (e.g., [Wehmuth and Ziviani, 2013, Dissler et al., 2016, Kim and Wu, 2013])	++ to +++	++	+ to +++

Thesis contribution:

3 approximation algorithms	+++ to ++++	+++	+

$\Longrightarrow$ A good cost-accuracy trade-off

My Contributions

- 3 distributed algorithms:
  - k-BFS SumSweep
  - ABC-Center (two versions)
  - Probabilistic Counter based Central Leader Election (PC2LE)
- Inspired from existing external-graph analysis algorithms
- All based on intuitive heuristics
- Experimental evaluation of the accuracy
- Formal analysis of the performance:

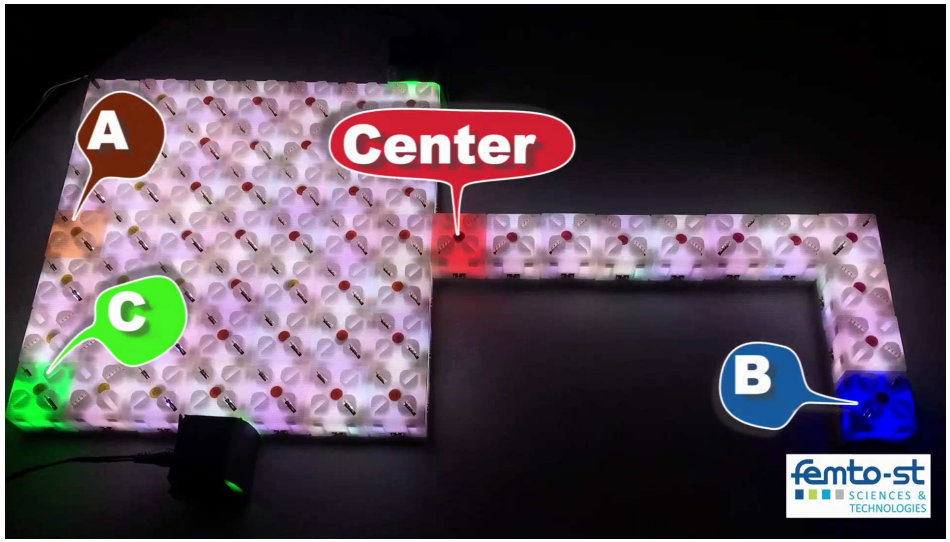
Name	Type of center	Time	Memory (per module)	Message
k-BFS SumSweep	center, centroid	$O(k \times d)$	$O(\Delta)$	$O(m \times n^2)$
ABC-CenterV2	center	O($\#steps \times d$)	$O(\Delta)$	$O(m \times n^2)$
PC2LE	center, centroid	O(d)	$O(\Delta +$ |probabilistic counter|)	$O(m \times n^2)$

Notation:
$n = \#$modules, $m = \#$ links, $d =$ diameter, $\Delta =$ maximum number of neighbors

Subsection Outline

General Idea

- Extends the sequential MiniMax algorithm [Handler, 1973] for tree graphs
- Idea: the center stands at the middle of a diameter (i.e., longest path)



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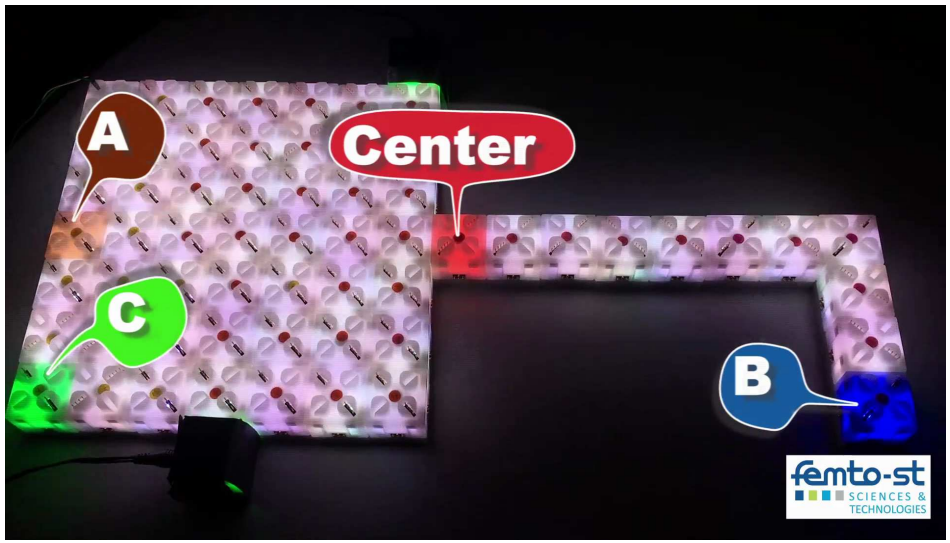
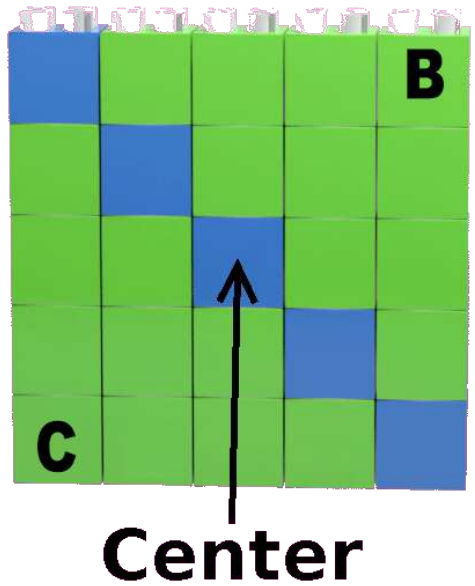


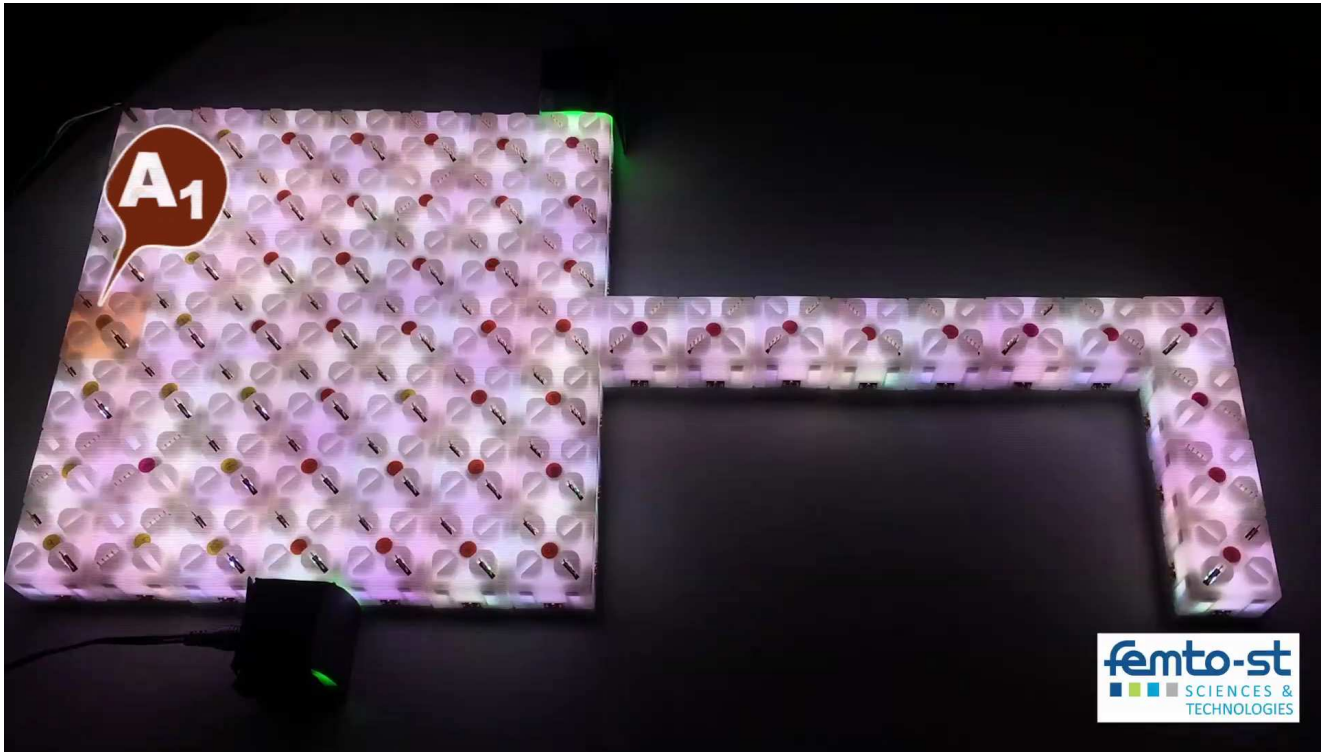


Algorithm

Candidates $\leftarrow$ *all modules*;
while $|Candidates| > 2$ **do**
  $A \leftarrow v_i \in Candidates$; // A is a random candidate
  $B \leftarrow v_i \in \underset{v_j \in Candidates}{\text{argmax}} \; d(A, v_j)$; // B a farthest candidate from A
  $C \leftarrow v_i \in \underset{v_j \in Candidates}{\text{argmax}} \; d(B, v_j)$; // C a farthest candidate from B
  // Most equi-distant nodes from B to C remain candidate:
  $Candidates \leftarrow \underset{v_j \in Candidates}{\text{argmin}} \; |d(B, v_j) - d(C, v_j)|$;
  // B and C are eliminated (if not already purged by the previous line):
  $Candidates \leftarrow Candidates - \{B, C\}$;
end
central $\leftarrow v_i \in Candidates$; // a random candidate

Single-source shortest paths are computed using distributed breadth-first network traversals (based on [Cheung, 1983]).

Examples - One-step 2D Shape



*60 Blinky Blocks

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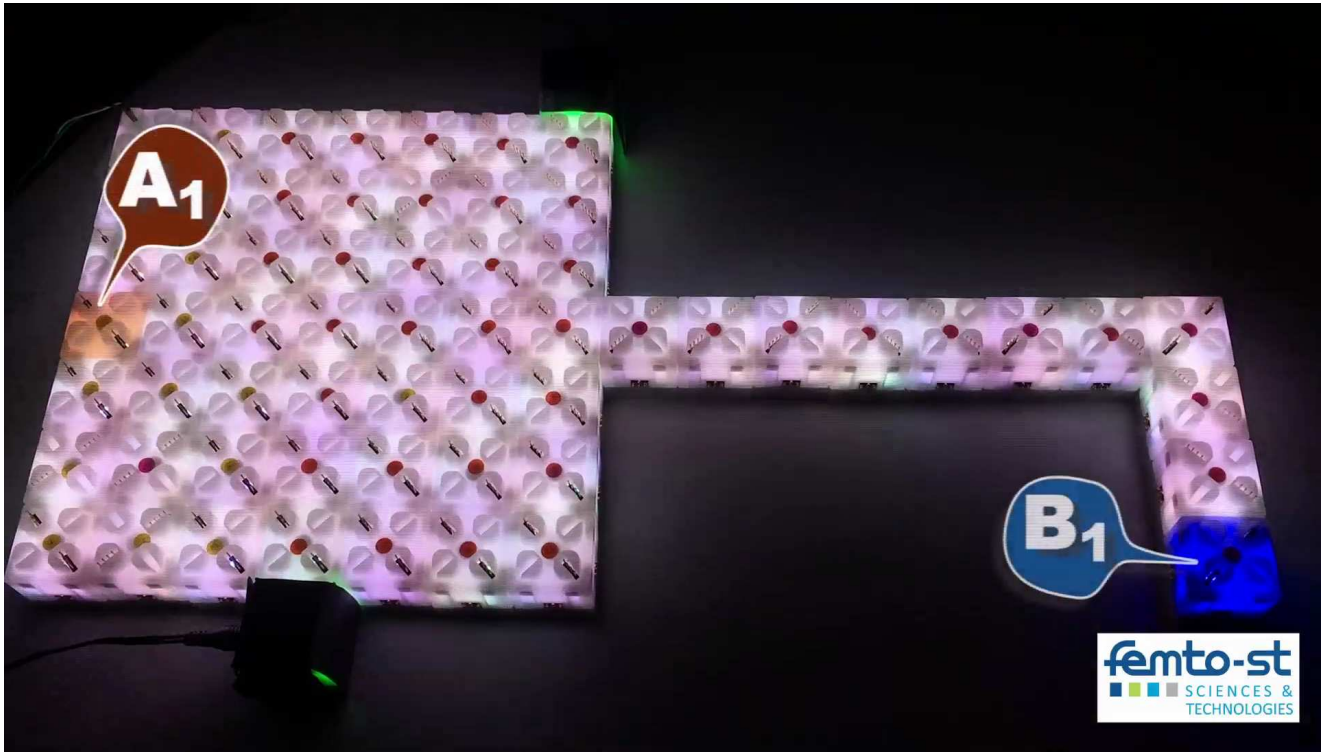

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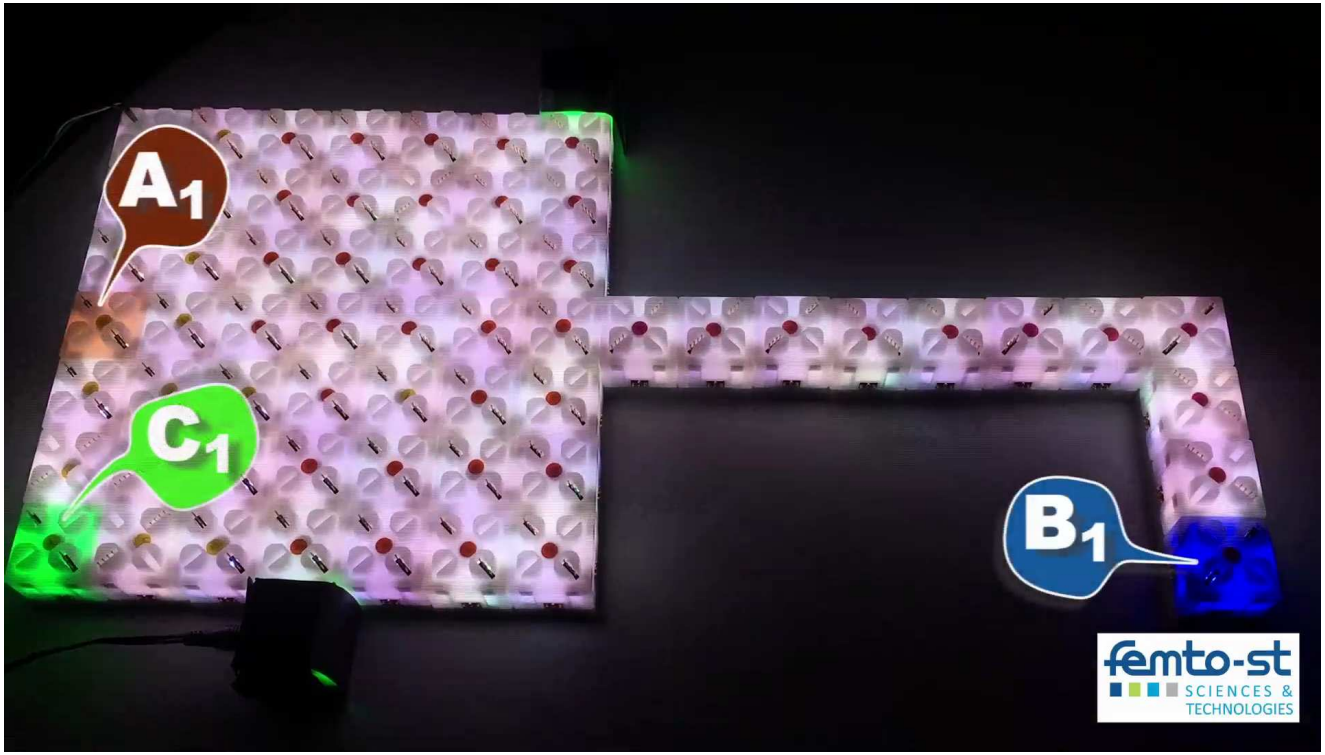

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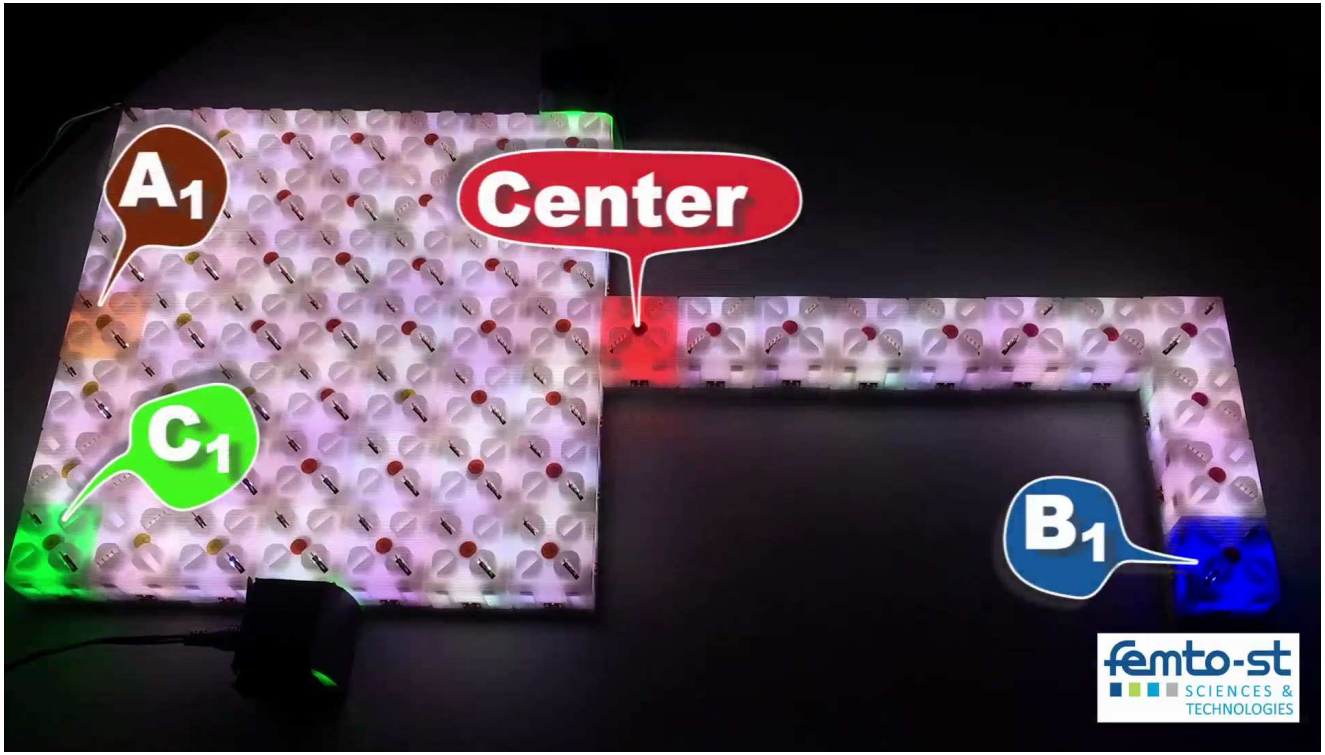

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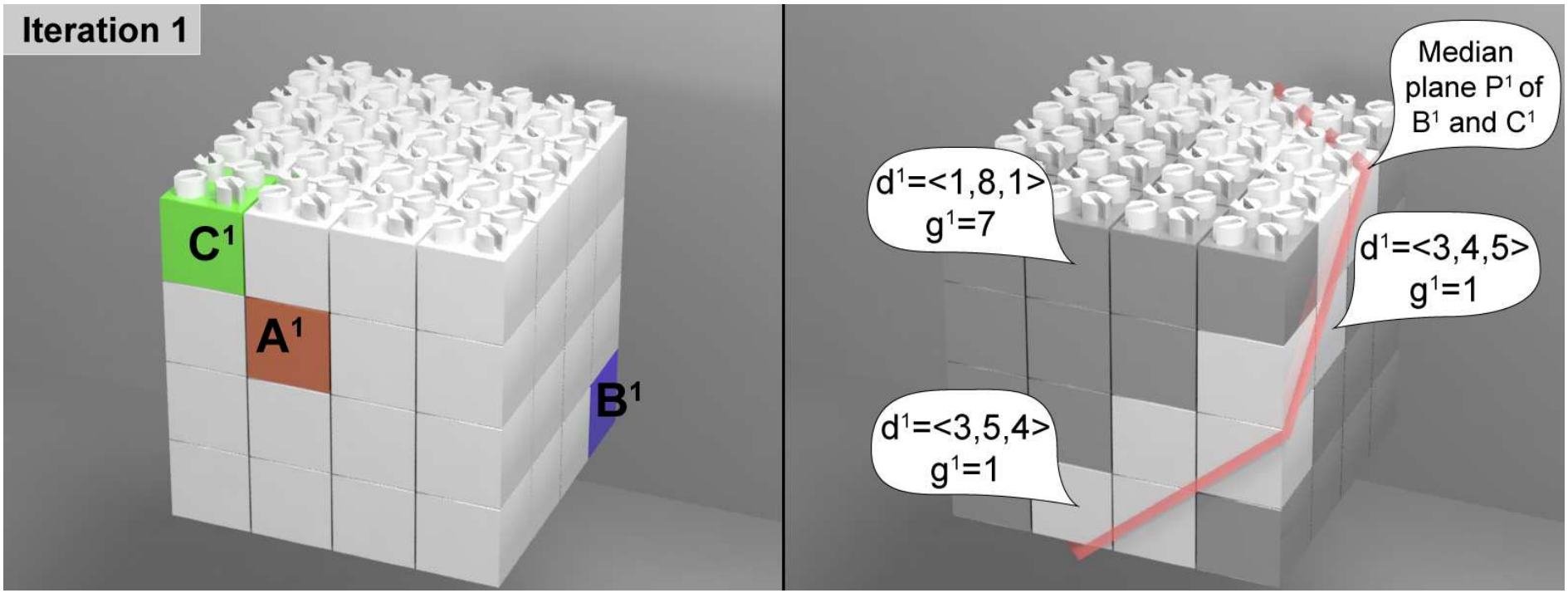
Examples - More complex



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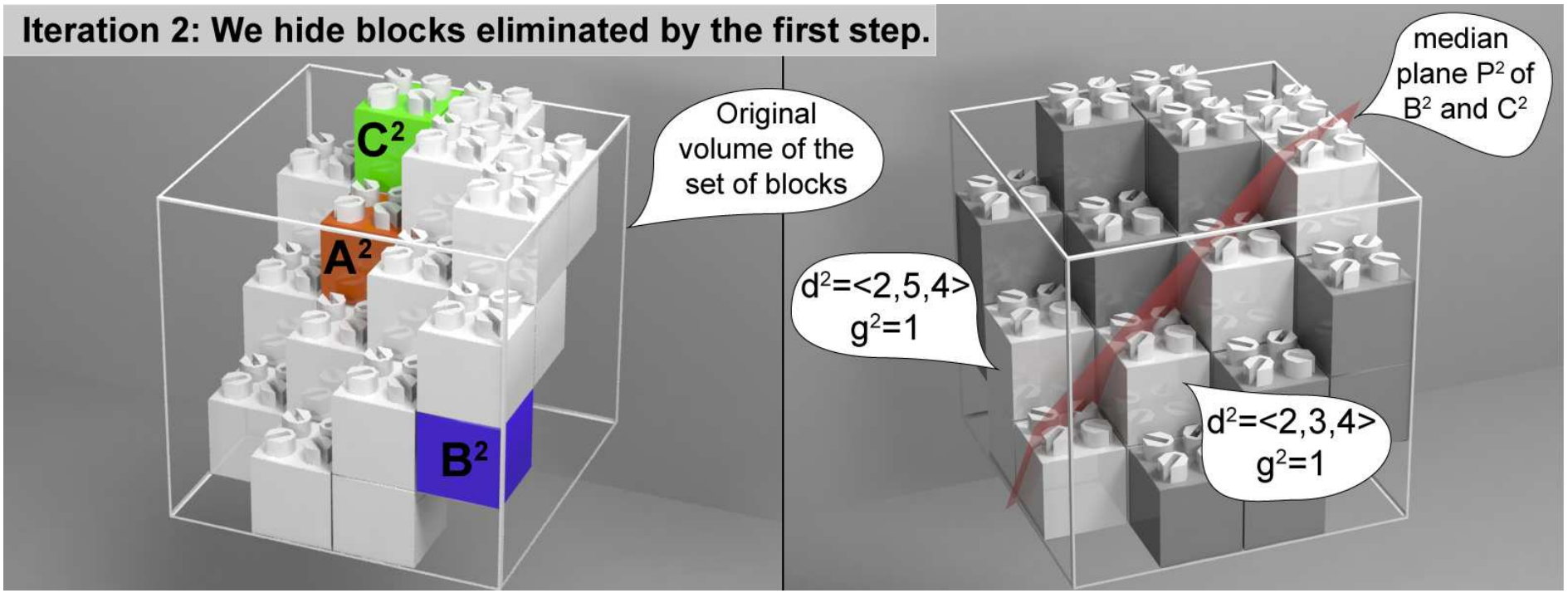

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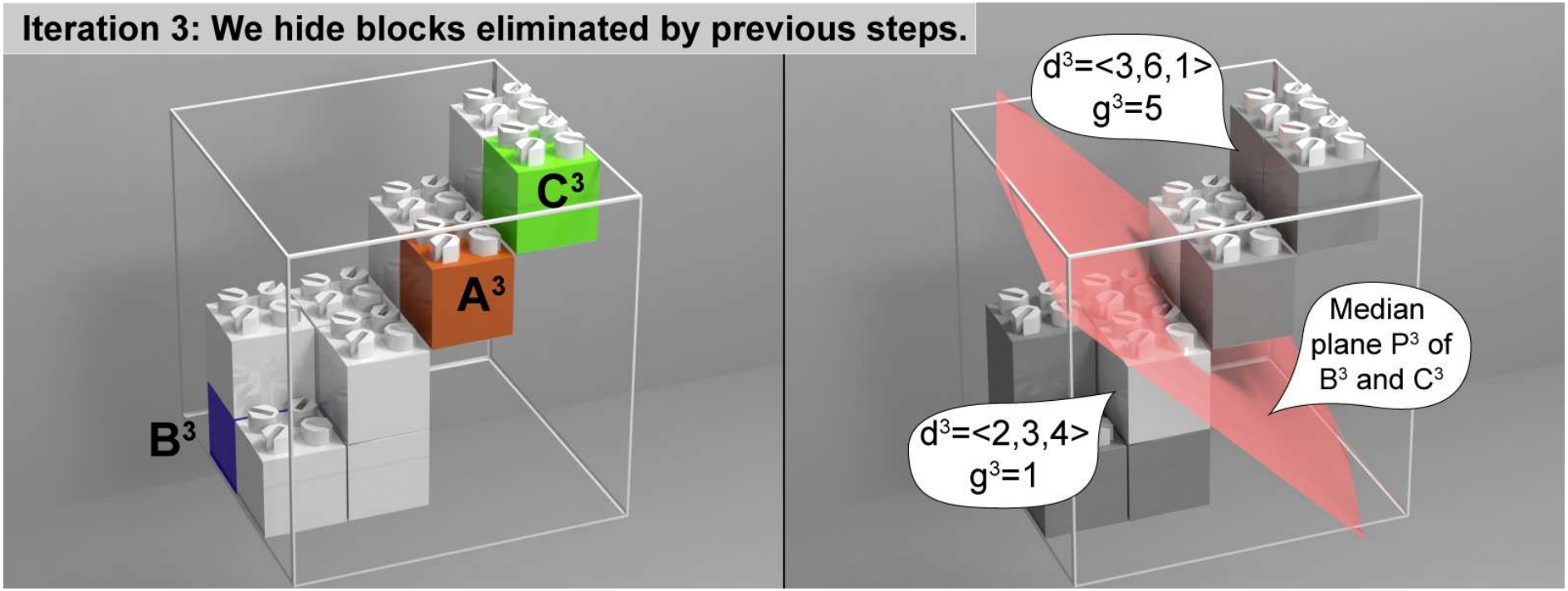

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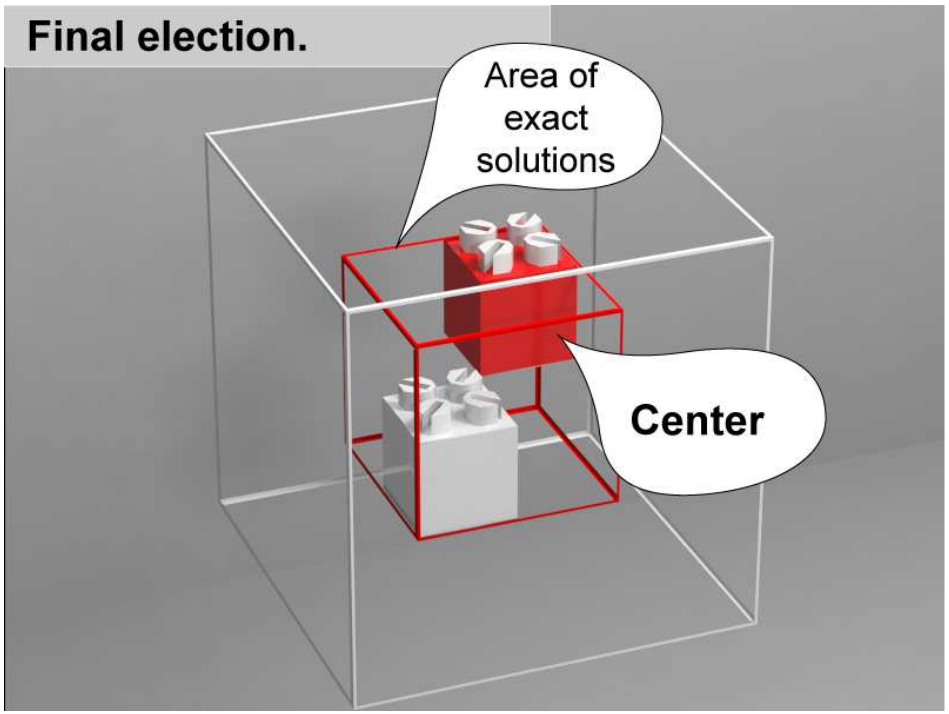

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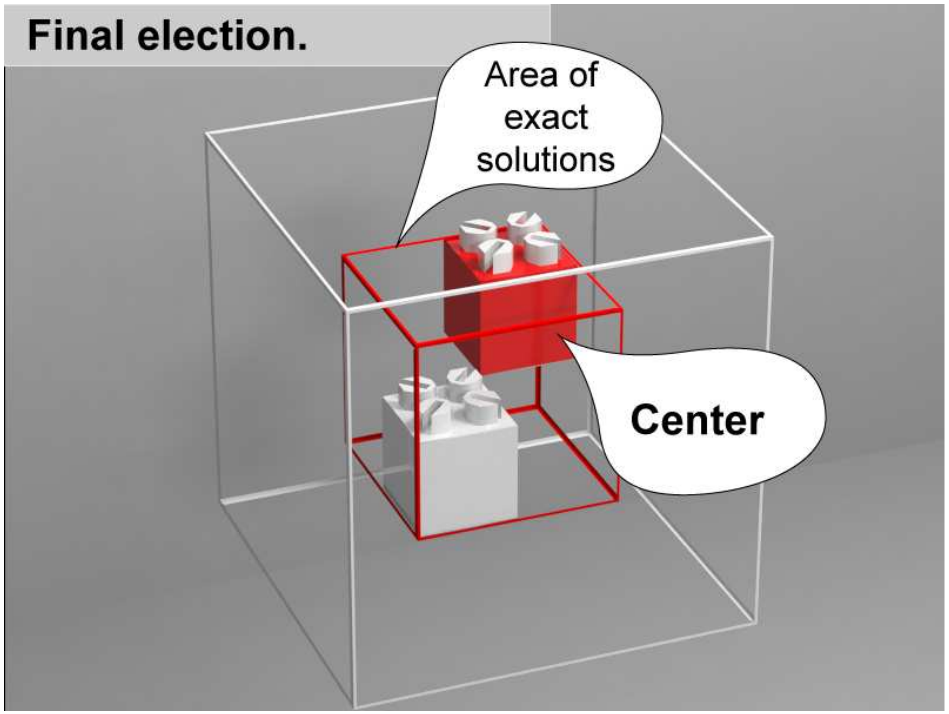
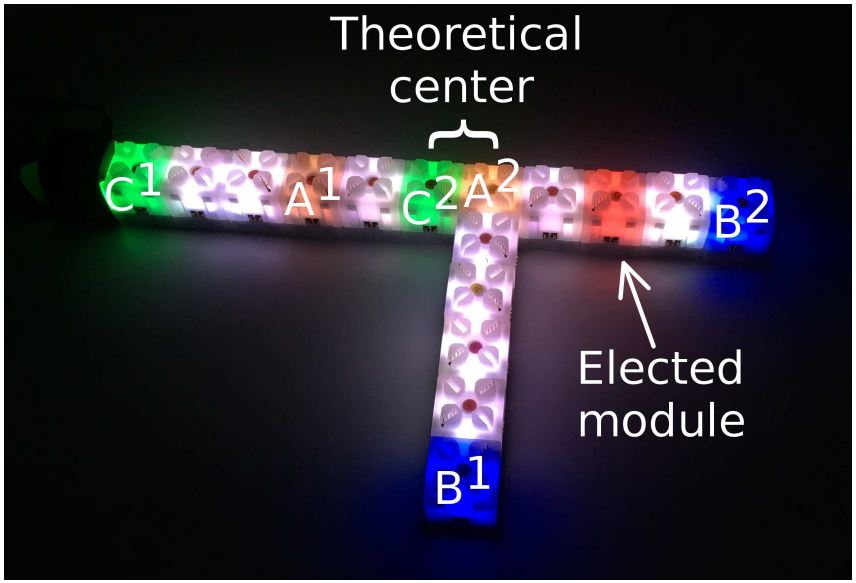


$\Longrightarrow$ # steps increases with the thickness of the diameter

$\Longrightarrow$ ABC-Center is more efficient in low-degree networks

Tricky Case for Future Work



ABC-CenterV1/V2

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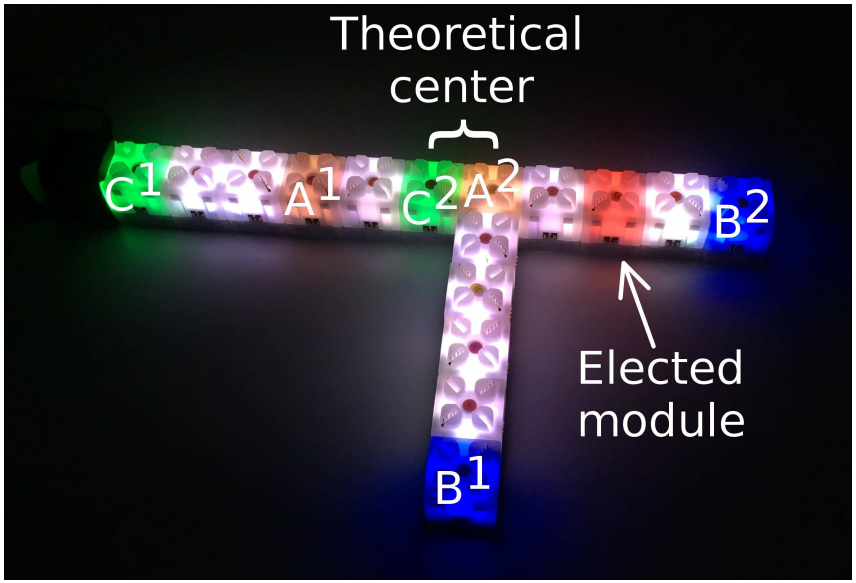

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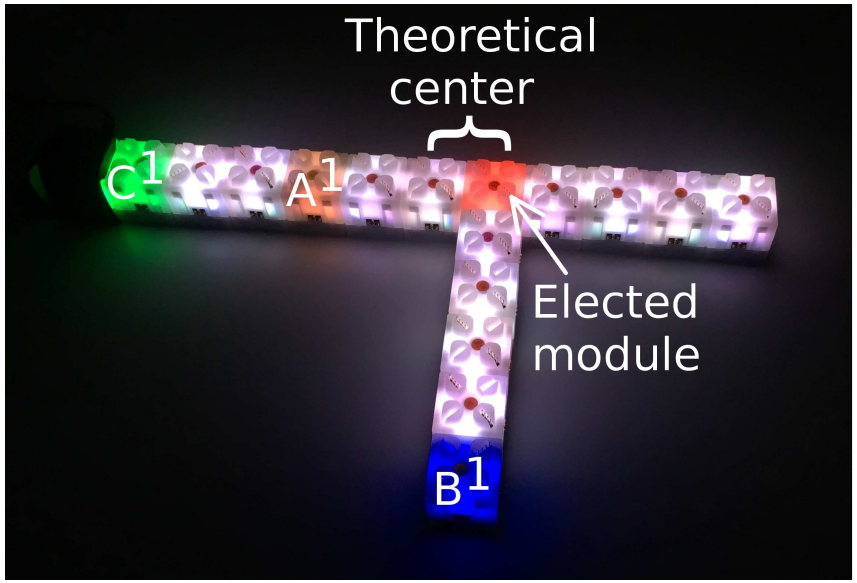

Envisioned but abandoned approach

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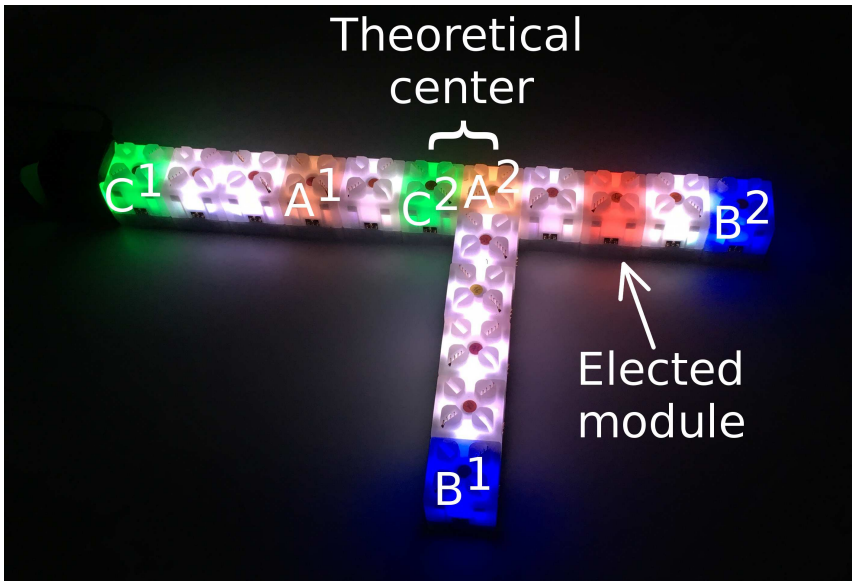
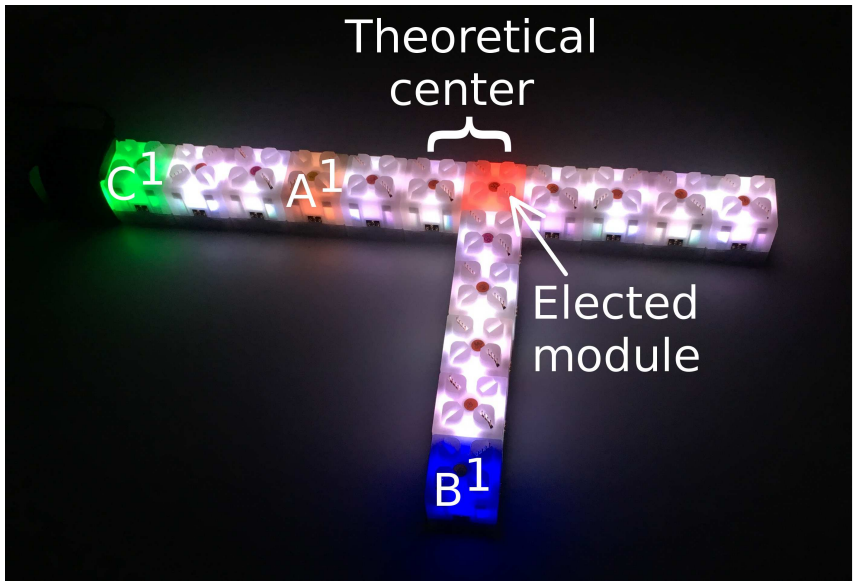


ABC-CenterV1/V2



Envisioned but abandoned approach

$\Longrightarrow$ The envisioned approach solves this case but leads to less accuracy in experiments with random systems

$\Longrightarrow$ This specific case should be investigated in future work!

Subsection Outline

ABC-CenterV1 on Hardware

VisibleSim Simulator Fidelity

Statistical simulation model based on measurements

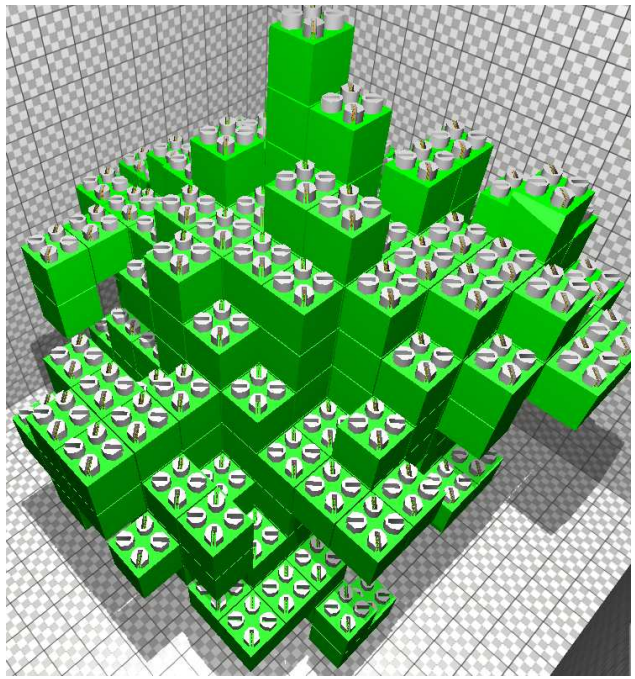
- Processing time
- Communication time

Shape	Size (module)	average ABC-CenterV1 execution time $\pm$ standard-deviation (ms)		Relative average simulation precision
		Hardware	Simulator	
Line	5	234 ± 1	244 ± 3	95.7%
	10	545 ± 5	544 ± 5	99.8%
	50	2873 ± 23	2885 ± 17	99.6%
Square	9	598 ± 45	588 ± 14	98.3%
	25	1117 ± 30	1119 ± 27	99.8%
	49	1684 ± 48	1686 ± 44	99.9%
Cube	27	1229 ± 56	1214 ± 31	98.8%
	64	1927 ± 51	1941 ± 33	99.3%
Dumbbell	59	1262 ± 56	1252 ± 57	99.2%

$\Longrightarrow$ VisibleSim accurately simulates our algorithm on the Blinky Blocks

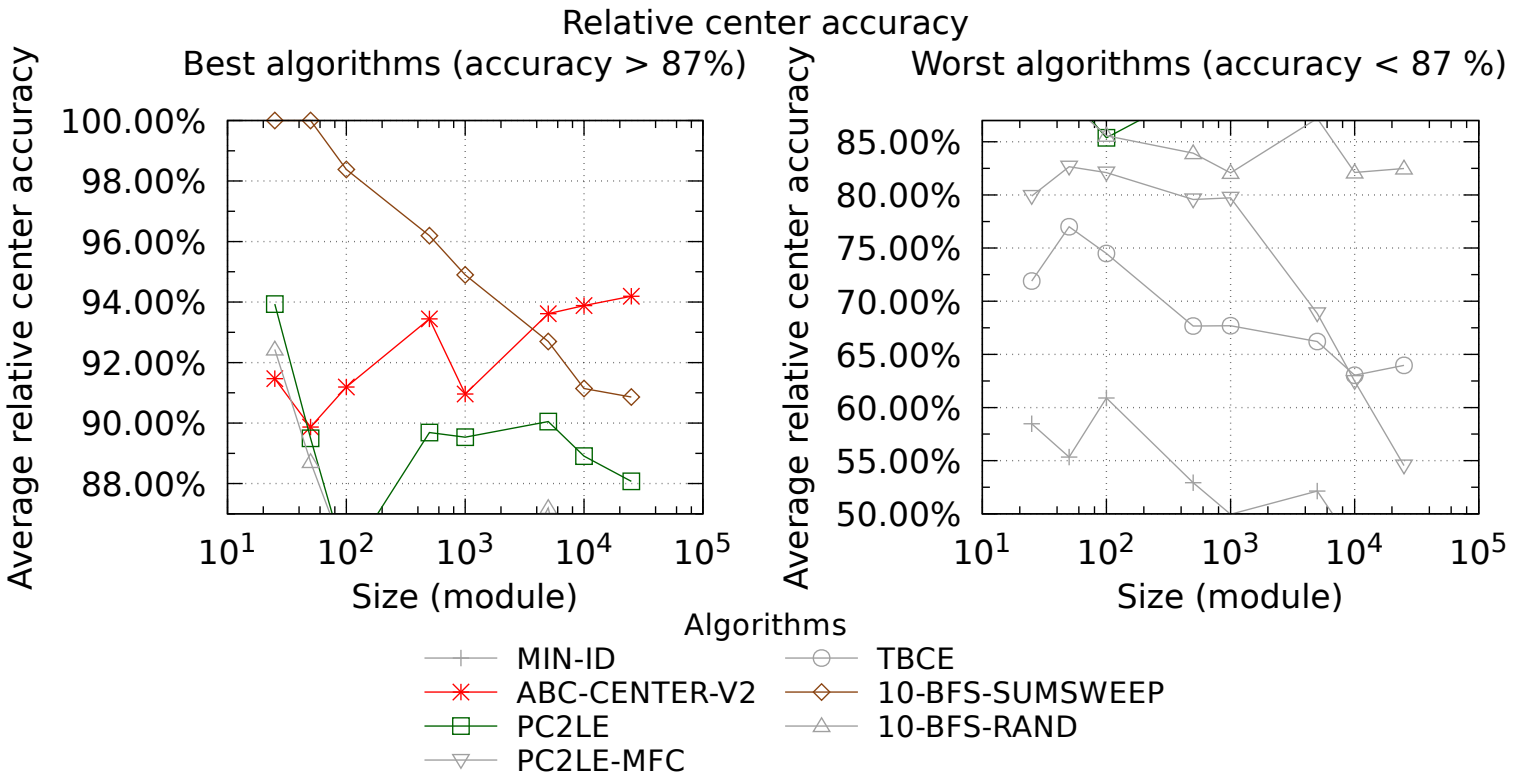
Simulation Evaluation

- Simulations using VisibleSim
- Comparisons with other algorithms
  - Random: MIN-ID [Raynal, 2013]
  - Exhaustive: BARYCENTER [Mamei et al., 2005]
  - Approximations:
    - TBCE [Kim and Wu, 2013]
    - k-BFS-RAND, our distributed version of [Eppstein and Wang, 2001]
    - PC2LE with [Garin et al., 2012] 's probabilistic counter
- Systems
  - Random compact shapes
  - Different sizes: 10 to 25,000 modules
  - Statistics on multiple independent runs
- Evaluation criteria
  - Accuracy
  - Cost
    - Execution time
    - Number of messages
    - Memory usage



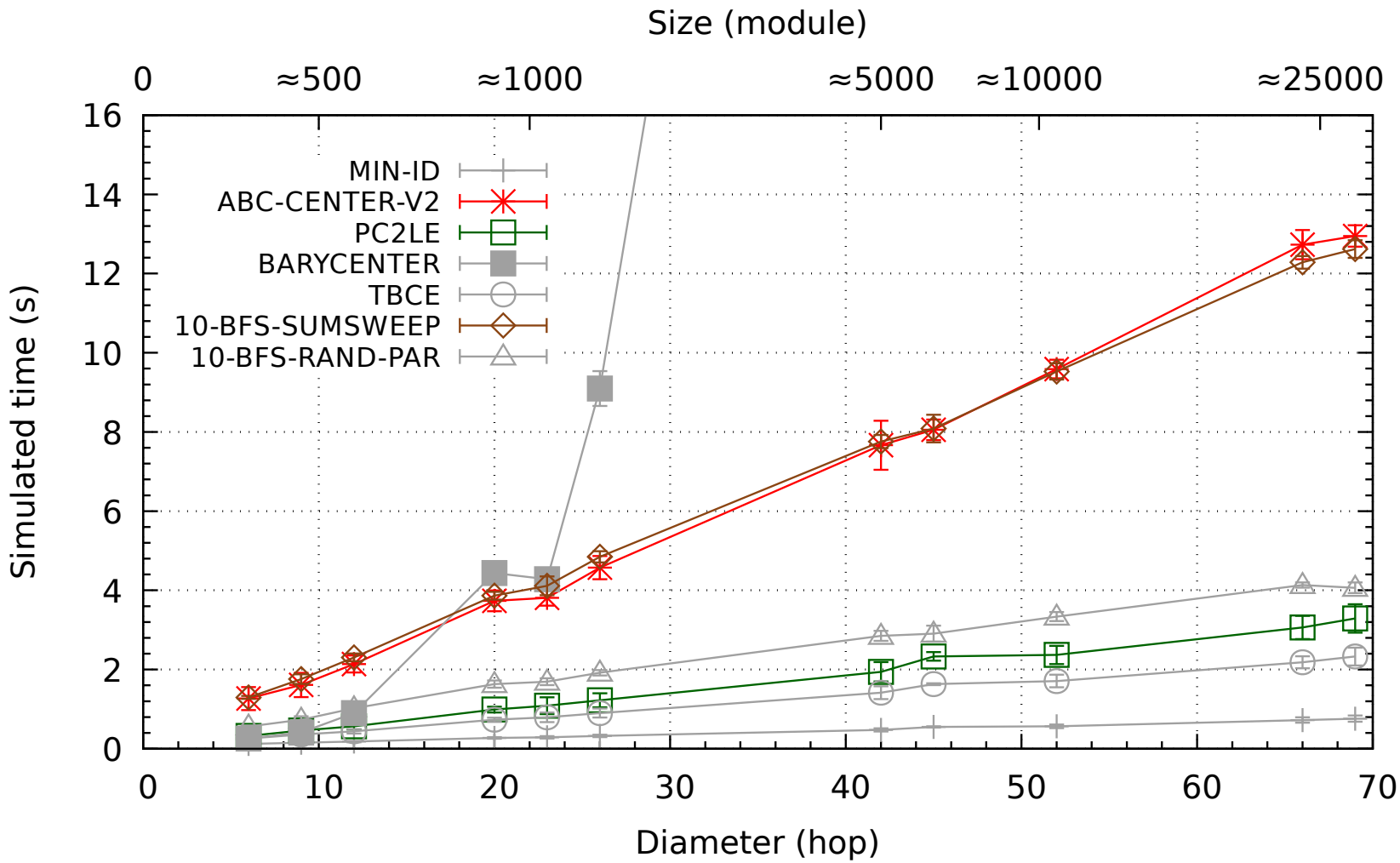
Relative accuracy

$$relative\ center\ accuracy = 1 - \left| \frac{ecc(center) - ecc(elected\ node)}{ecc(center)} \right|$$



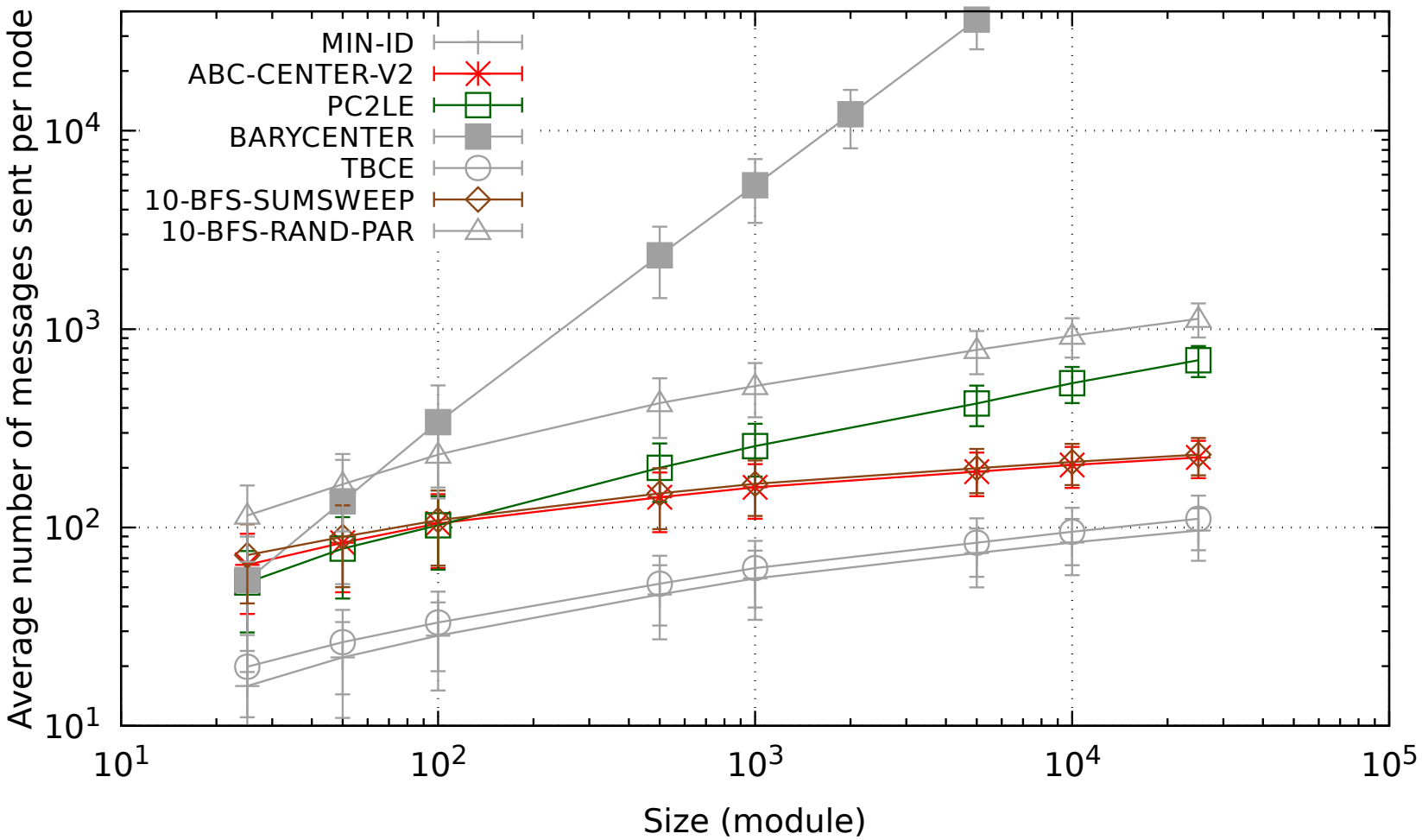
$\Longrightarrow$ Our algorithms:
most precise approximation algorithms (accuracy $> 85\%$)

Execution Time



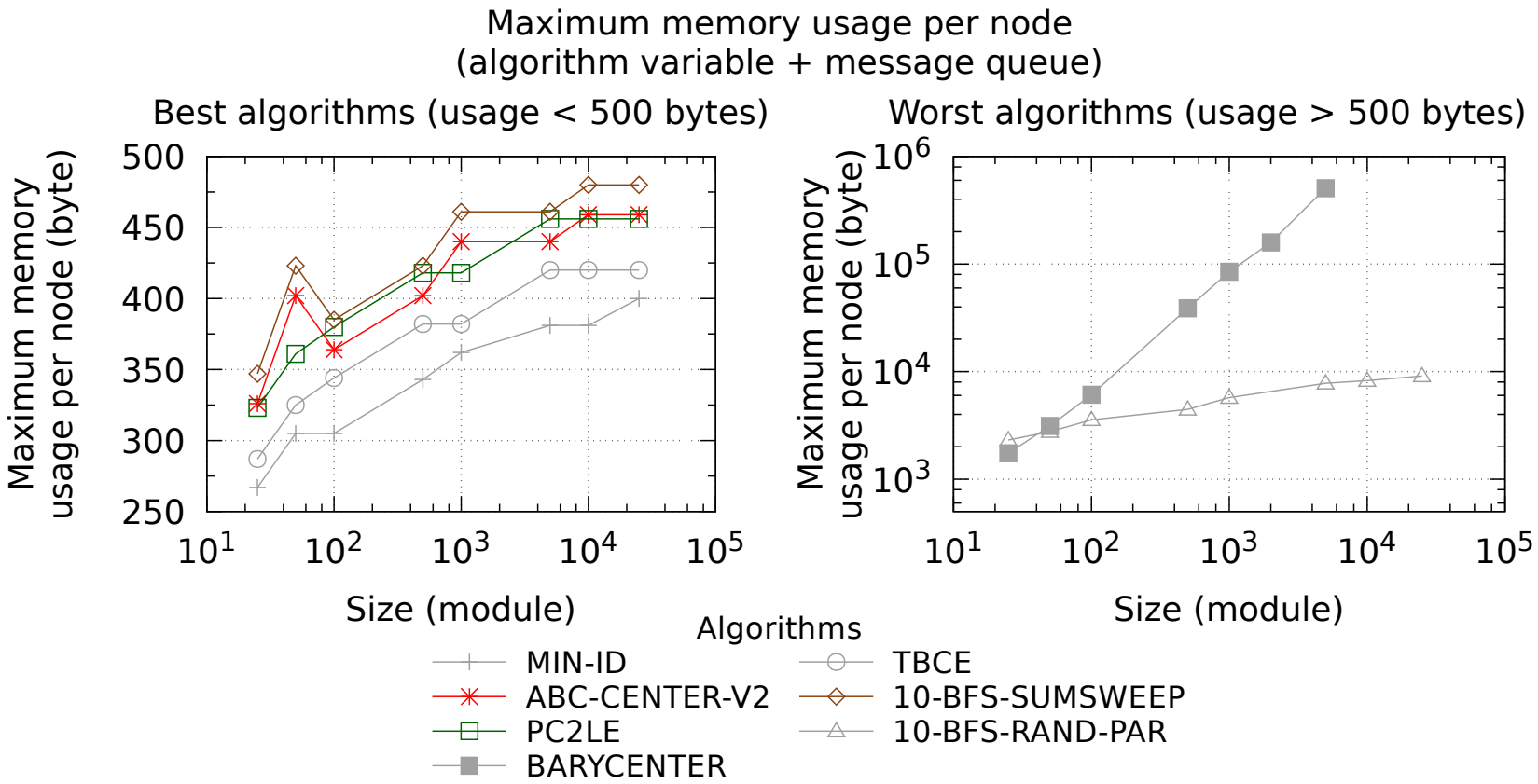
$\Longrightarrow$ A good trade-off between cost and accuracy

Average number of messages per module



$\Longrightarrow$ A good trade-off between cost and accuracy

Memory usage



$\Longrightarrow$ Our algorithms have a bounded and limited memory usage ($<$ 500 bytes per module)

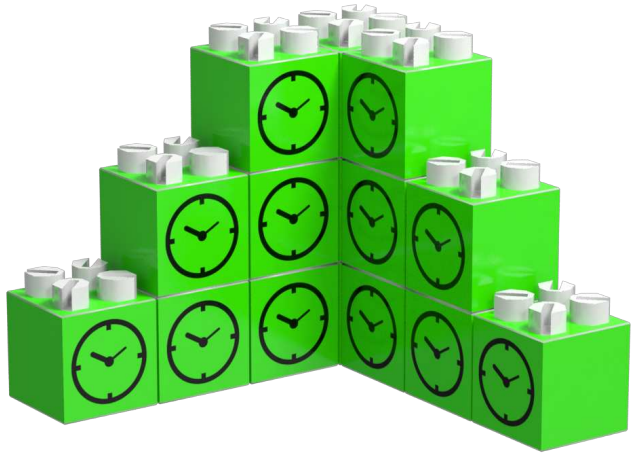
Conclusion

- 3 efficient distributed centrality-based leader election algorithms
  - k-BFS SumSweep, ABC-Center and PC2LE
- Robustness to network dynamics
- Formal analysis of the performance (time, message and memory)
- Evaluation
  - Hardware: 5 to 64 modules
  - Simulations: 10 to 25,000 modules
    - Most precise approximation algorithms ($>$ 85% relative center accuracy)
    - Good cost-accuracy trade-off
- Limits
  - Experimental evaluation of the accuracy
  - Bad cases?
  - Efficiency in other platforms with different network structures?
    - Our algorithms: inspired from external-graph analysis algorithms used to study large-scale real-world networks (e.g., YahooWeb, AS networks)

Section Outline

Problem

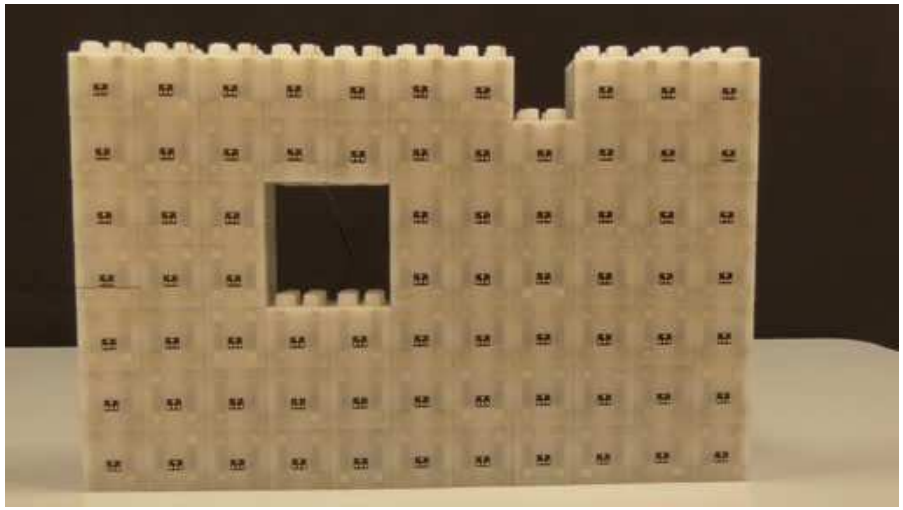
- Problem: maintain a global timescale through the system



- Challenges:
  - Imperfect hardware clocks (clock drift, skew, offset and noise)
  - Handling communication delays

Motivation

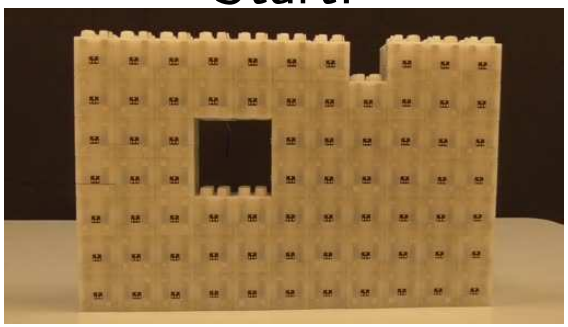
Distributed coordination (e.g., distributed bitmap scroller)



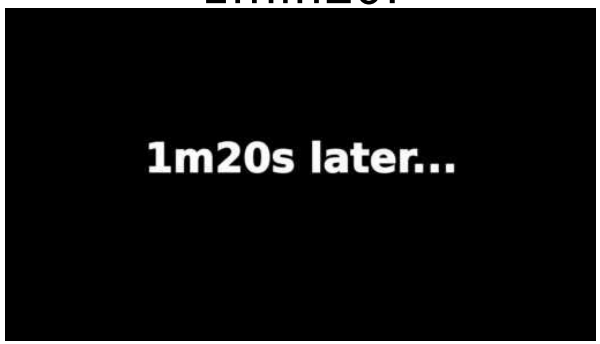
72-Blinky-Blocks scroller synchronized with our protocol (MRTP)

Unsynchronized scroller:

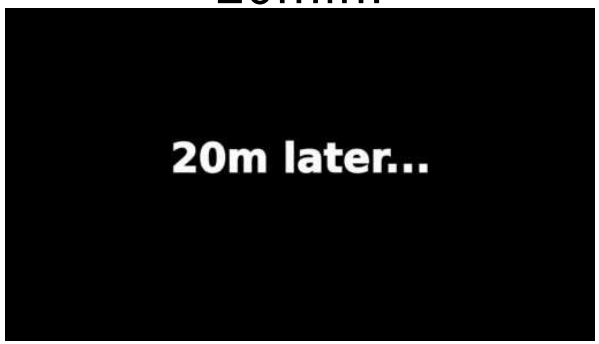
Start:



1min20:



20min:



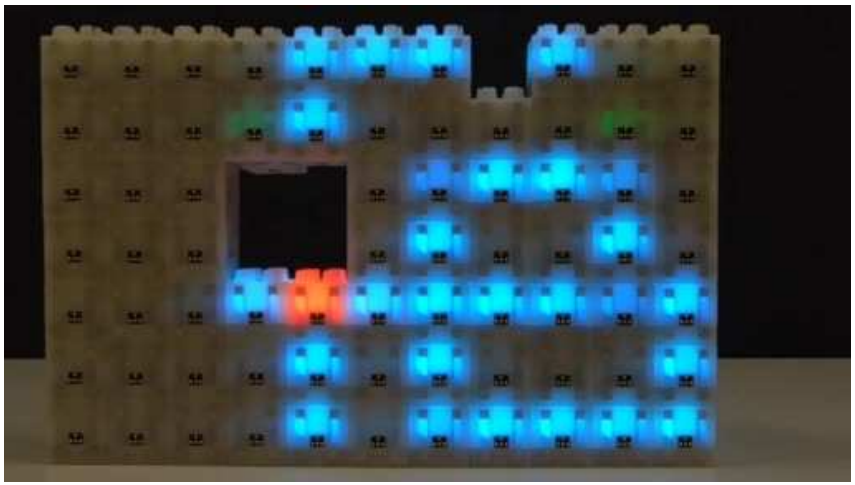
$\Longrightarrow$ This application requires a global timescale

Assumptions

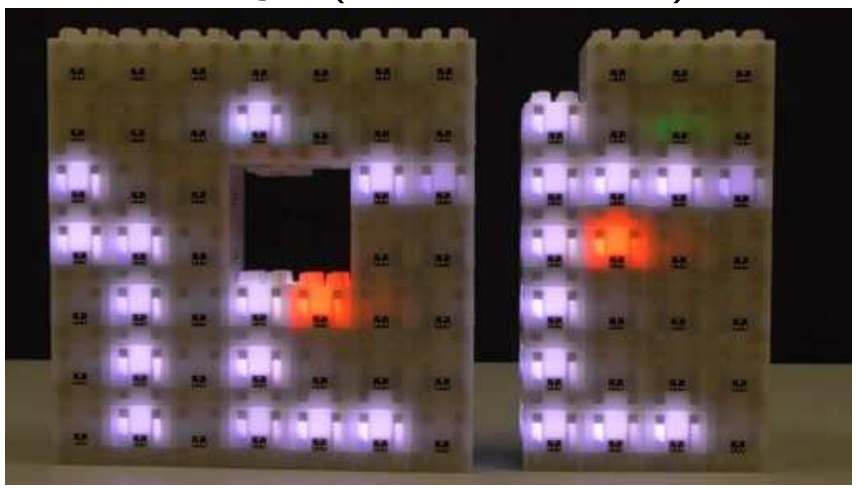
Illustrated on the Blinky Blocks modular robot, but suitable for networked embedded devices with:

- Local clocks
  - Nearly identical precision/resolution (potentially poor)
    - Blinky Blocks: 1% precision, 1 ms resolution
- Network
  - Neighbor-to-Neighbor communications
  - Potentially: large network size and large diameter
  - Fairly stable

Split:



Merge (after 2 hours):



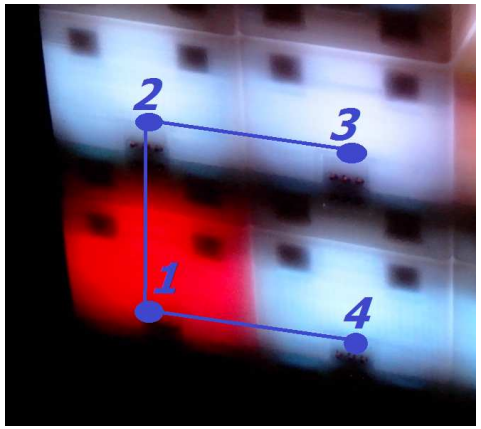
Related Works

Name	Domain	Architecture	Infrastructure	Synchronization Technique	Clock Skew Compensation
NTP [Mills, 1991]	Computer Networks	Master/Slave Master(s): pre-configured	Tree	(Multi-hop) round-trip messages with frame-level timestamps and statistics	Phase/frequency locked loops
PTP [IEEE, 2008]		Master/slave Master: best clock		Round-trip with low-level timestamps and per-hop delay compensation	
RBS [Elson et al., 2002]	Sensor Networks	Master/Slave	Clustering	Reference broadcast	Linear model
ATS [Schenato et al., 2011]		Fully distributed	/	Average-based consensus. Byte-level timestamps	
MTS [He et al., 2014a, He et al., 2014b]				Extremum-value based consensus. Byte-level timestamps	
TPSN + MLE [Leng and Wu, 2010]		Master/slave	Tree	Recursive per-hop synchronization. Round-trip with frame-level timestamps and statistics	
FTSP [Maróti et al., 2004]		Master/slave Master: minimum-id implicit election	/	Periodic asynchronous broadcasts. Byte-level timestamps and statistics	
PulseSync [Lenzen et al., 2015]				Fast flooding using broadcast. Byte-level timestamps	
Contribution: MRTP	Modular Robotic	Master/Slave Master: central	Breadth-first spanning-tree	Fast recursive per-hop synchronization. Compensation comm. delays: best for target system	Linear model

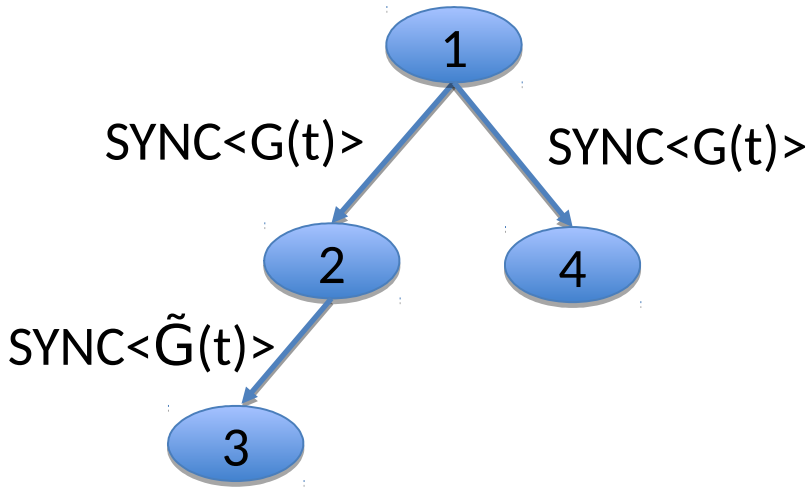
Subsection Outline

Contribution: The Modular Robot Time Protocol (MRTP)

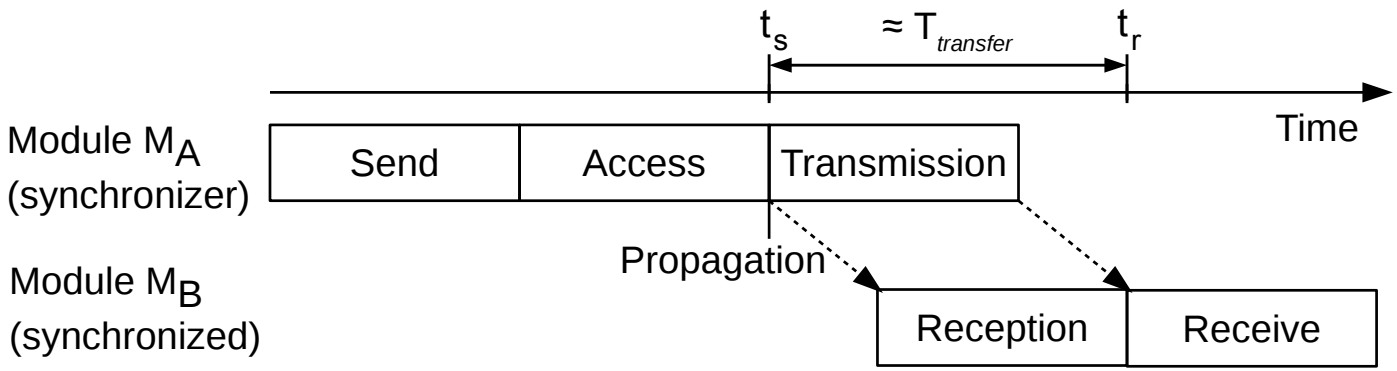
1. Initialization
   1. Central time master election
   2. Breadth first spanning-tree construction
2. Periodic synchronization
   - Best-suited method to compensate for communication delays
   - Clock skew compensation using linear regression

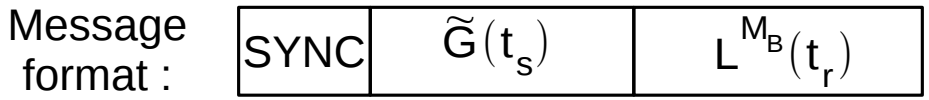


$G(t)$: global time, held by the time master
$\tilde{G}(t)$: disseminated estimation of $G(t)$



The Predictive Method to Compensate for Communication Delays





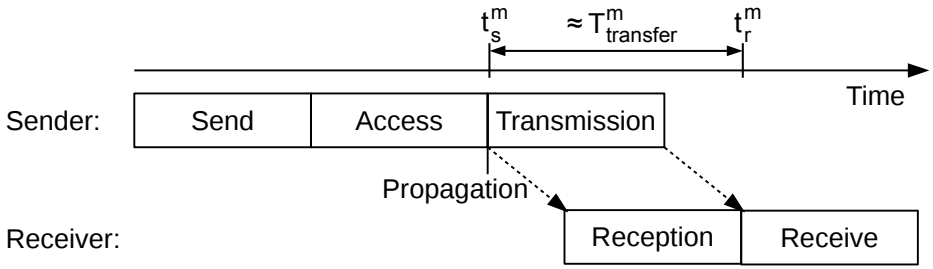
$$\tilde{G}(t_r) = \tilde{G}(t_s) + T_{transfer}$$

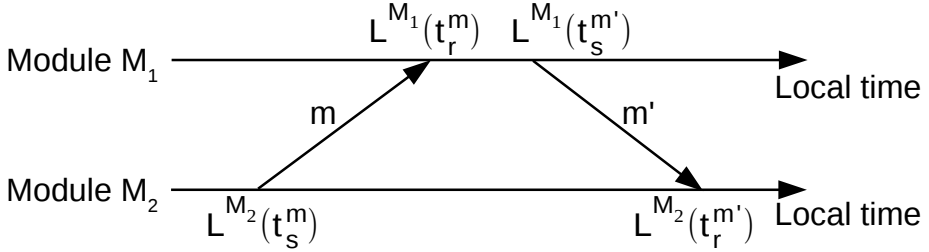
Linear regression on a window of synchronization points $< \tilde{G}(t), L^{M_B}(t) >$

$$G^{M_B}(t) = a^{M_B}(t) * L^{M_B}(t) + b^{M_B}(t)$$

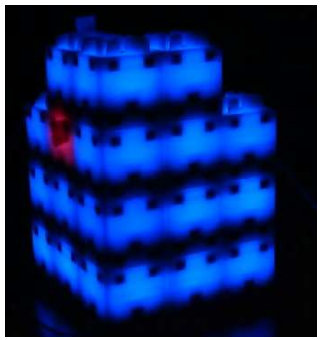
Subsection Outline

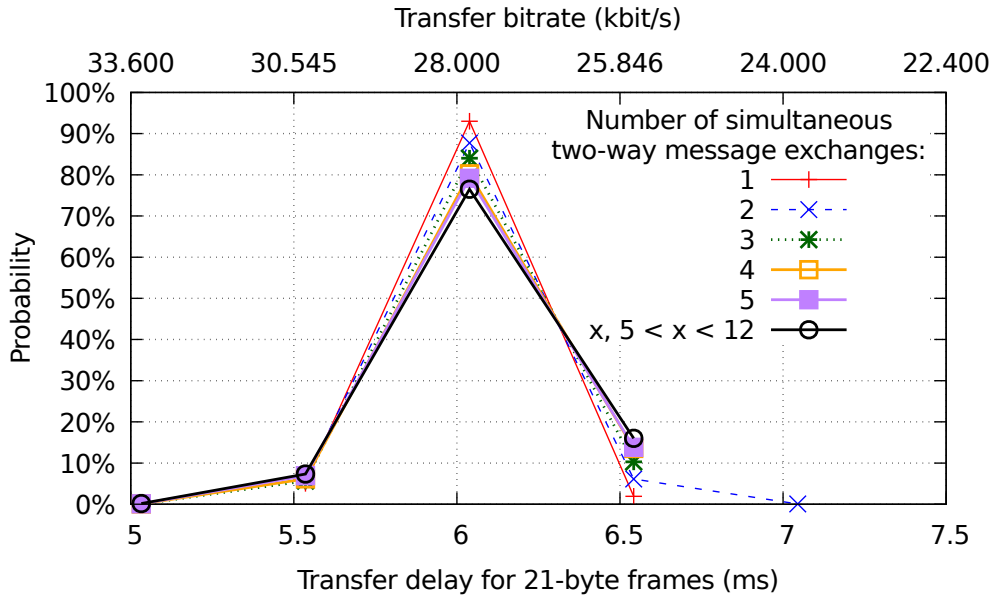
The Blinky Blocks Communication delays





$$T_{transfer} \approx \frac{(L^{M_2}(t_r^{m'}) - L^{M_2}(t_s^m)) - (L^{M_1}(t_s^{m'}) - L^{M_1}(t_r^m))}{2}$$





300,000 two-way exchanges

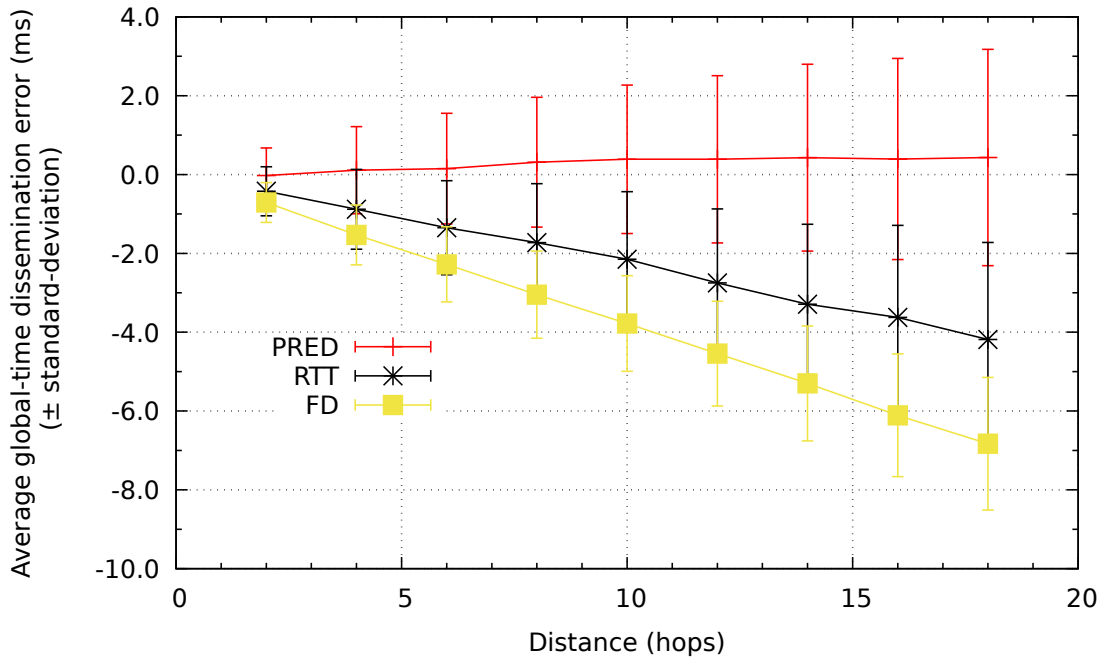
$$\overline{T_{transfer}} \approx \frac{\text{frame size}}{28.00}$$

$\Longrightarrow$ Predictable transfer delays

Best Method to Compensate for the Blinky Blocks Communication Delays?

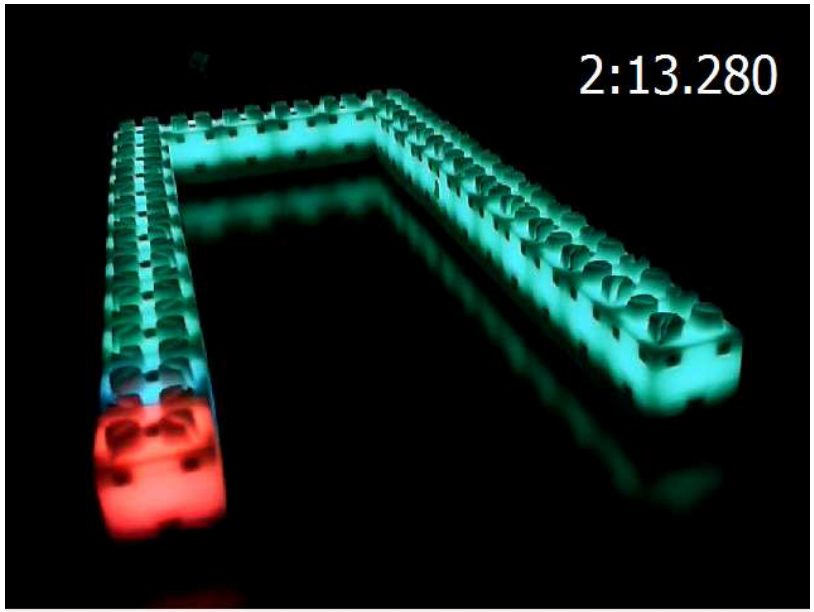
Methods applicable on the Blinky Blocks

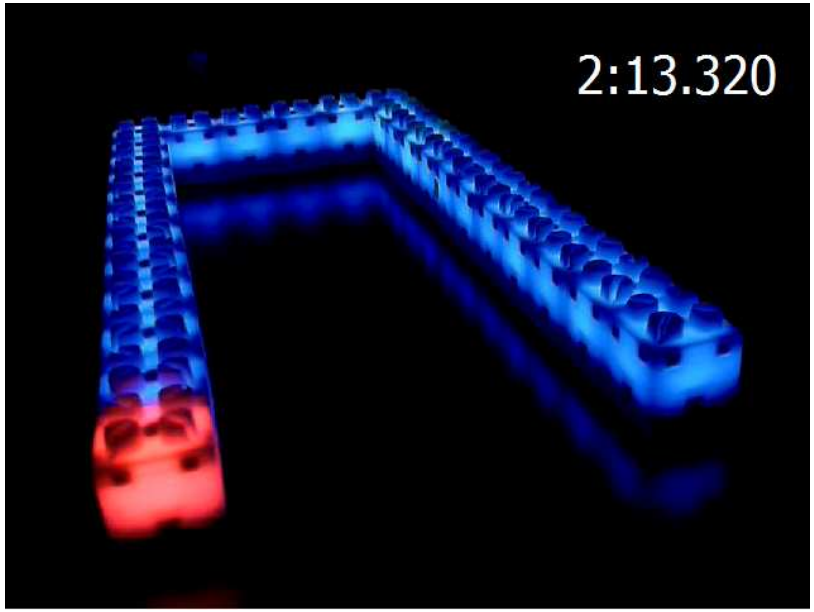
- Predictive (PRED)
- Round-Trip Time (RTT): used in TPSN
- Frame Delimiter (FD): used in ATS and MTS



$\Longrightarrow$ PRED is the most accurate and uses a single message per hop

Synchronizable Radius

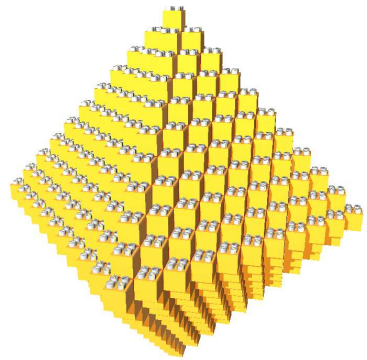




$\Longrightarrow$ The time master synchronizes modules in a 27-hop radius to $< 40ms$

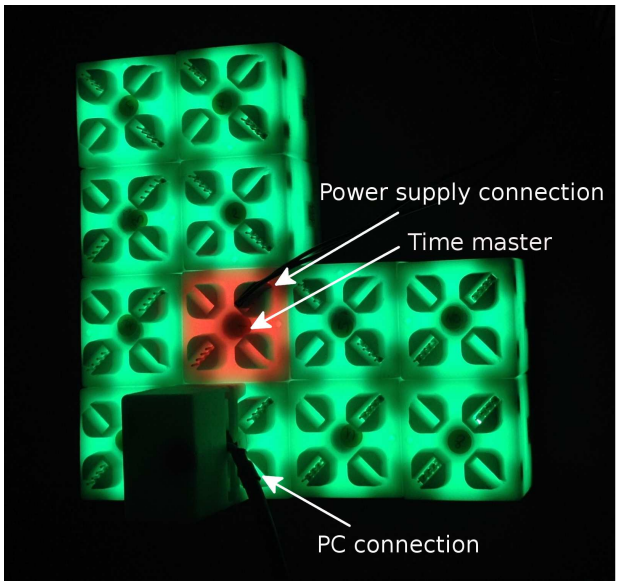
$\Longrightarrow$ Extrapolation: with a central time master, MRTP can synchronize the 27-hop-radius ball system (octahedral shape with 27,775 modules) to $< 40ms$.

$\Longrightarrow$ We will use simulations to show it!



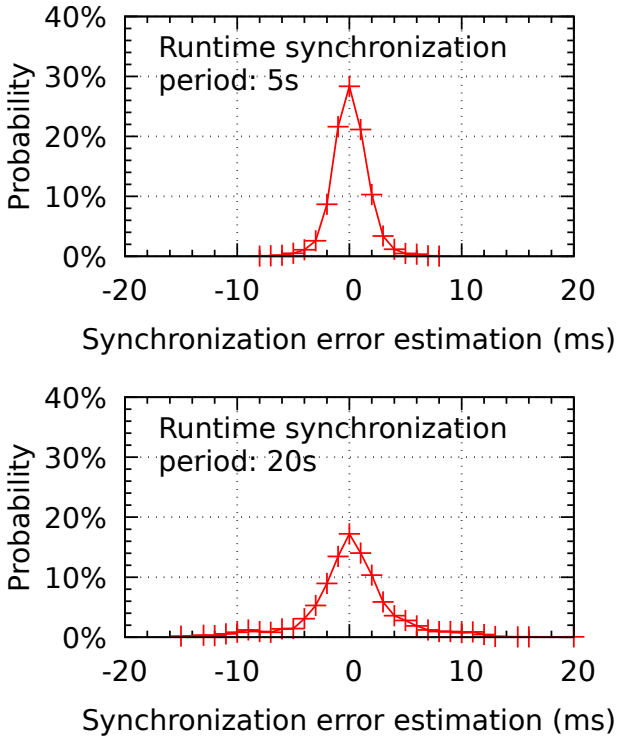
10-hop-radius ball
1561 Blinky Blocks

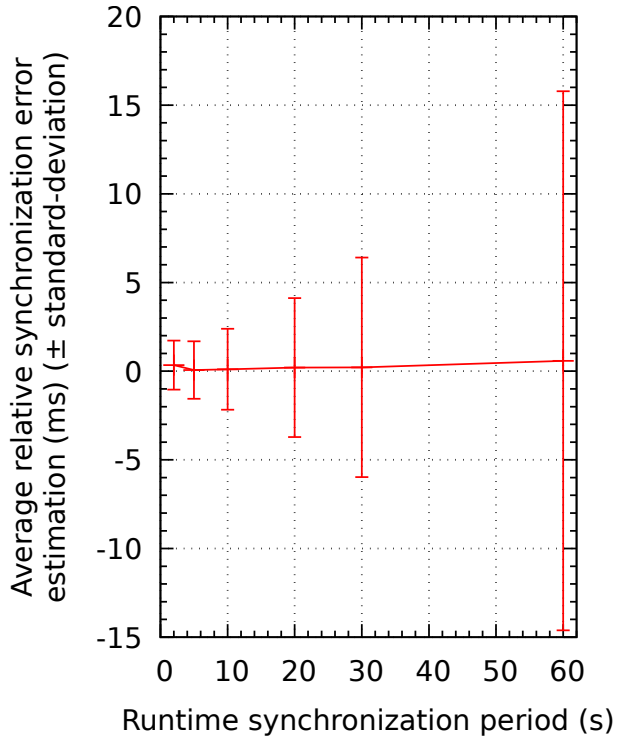
Impact of the Synchronization Period



Duration: 1 hour

Window size: 5





$\Longrightarrow$ MRTP keeps the system synchronized to a few milliseconds even with a synchronization period of 60 seconds

$\Longrightarrow$ The synchronization period depends on the desired precision. A long period uses less system resources.

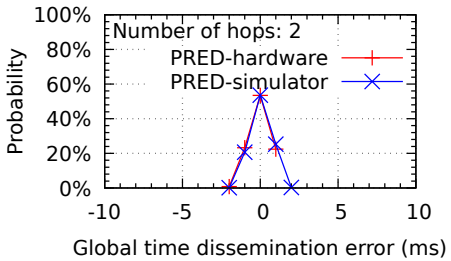
VisibleSim Simulator Fidelity

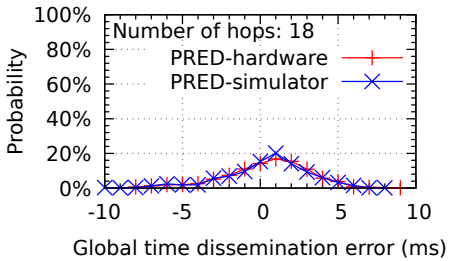
Statistical models:

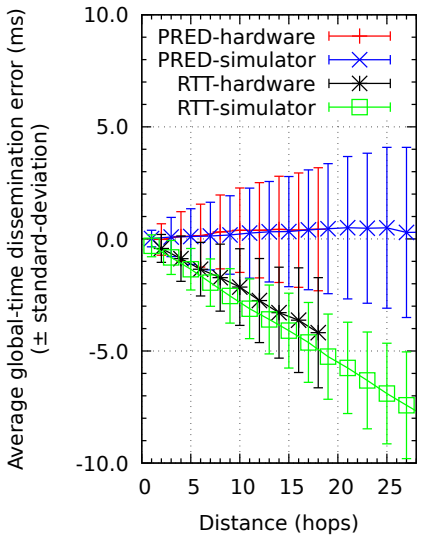
- Clock
  - Skew
  - Drift
  - Noise (replayed)
- Communication time
- Processing time

$\Longrightarrow$ Accurate simulation

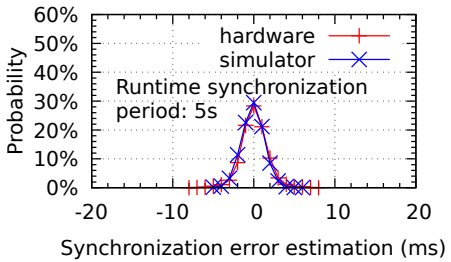
Global time dissemination error

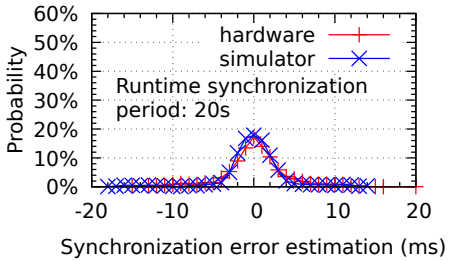


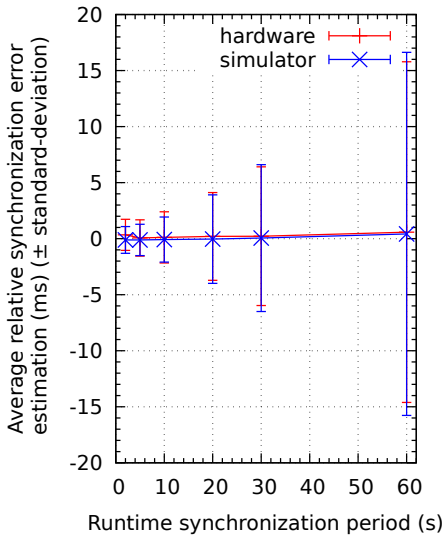




Synchronization precision



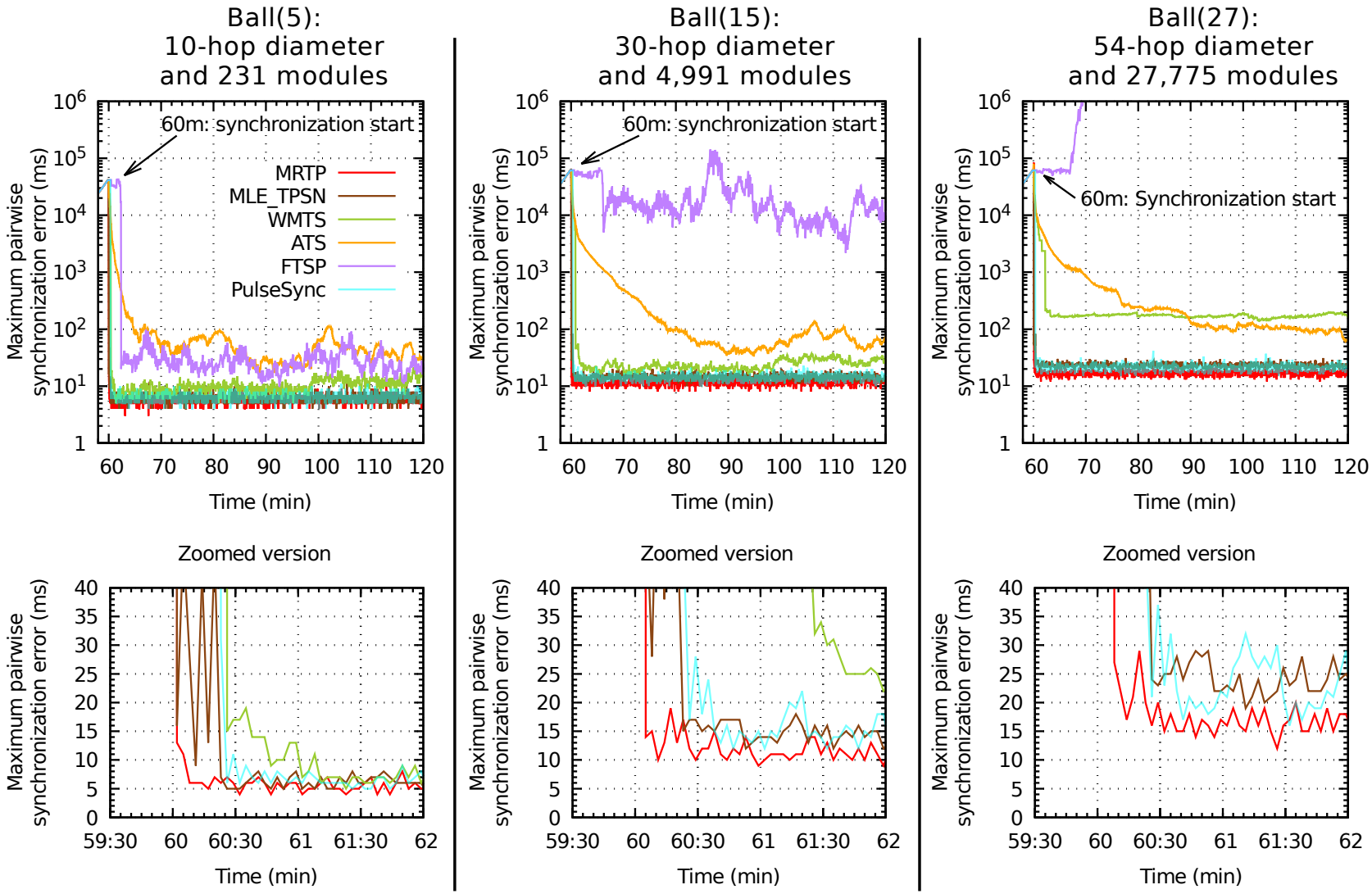




Simulation Evaluation

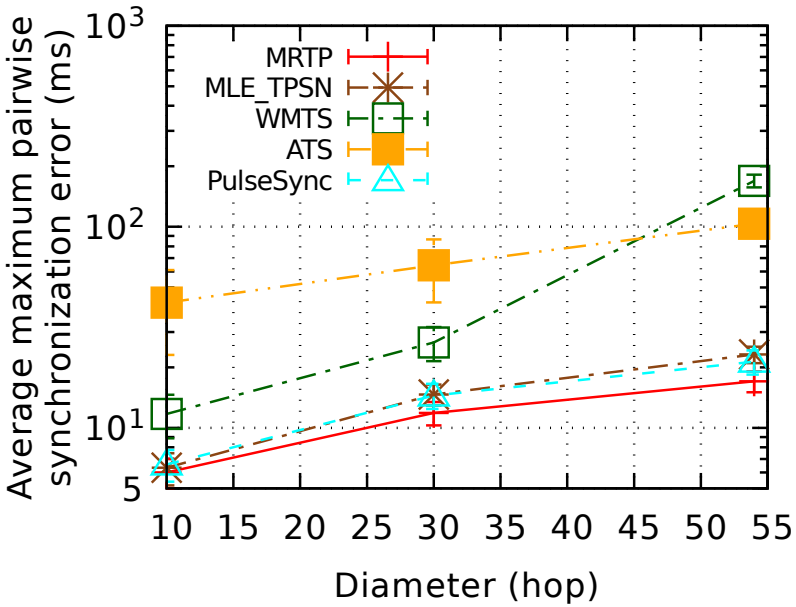
- Simulations using VisibleSim
- Comparisons with ported version of existing protocols
  - Decentralized: ATS [Schenato et al., 2011], WMTS [He et al., 2014b]
  - Master/Slave with tree: TPSN + MLE [Leng and Wu, 2010]
  - Master/Slave but infrastructureless: PulseSync [Lenzen et al., 2015]
- Experiments:
  - Ball systems (octahedrally-shaped)
    - Size: 231 to 27,775 modules
    - Diameter: 10 to 54 hops
  - Scenario:
    - Left unsynchronized for 1 hour
    - Then synchronization every 5 seconds during 1 hour
    - Measurements the maximum pairwise synchronization error every 3 seconds
- Evaluation criteria
  - Time of convergence
  - Synchronization precision
  - Messages

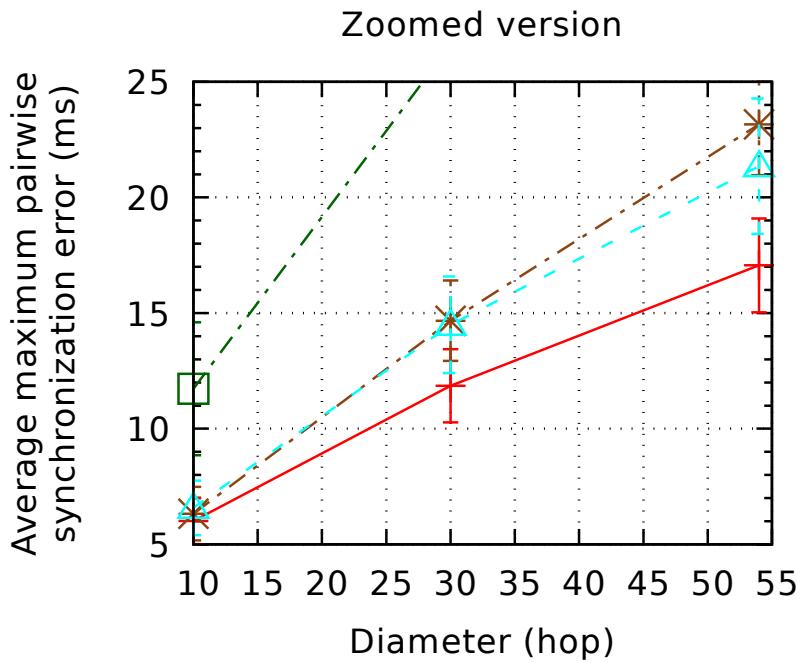
Convergence Time



$\Longrightarrow$ MRTP converges quickly

Synchronization Precision after Convergence

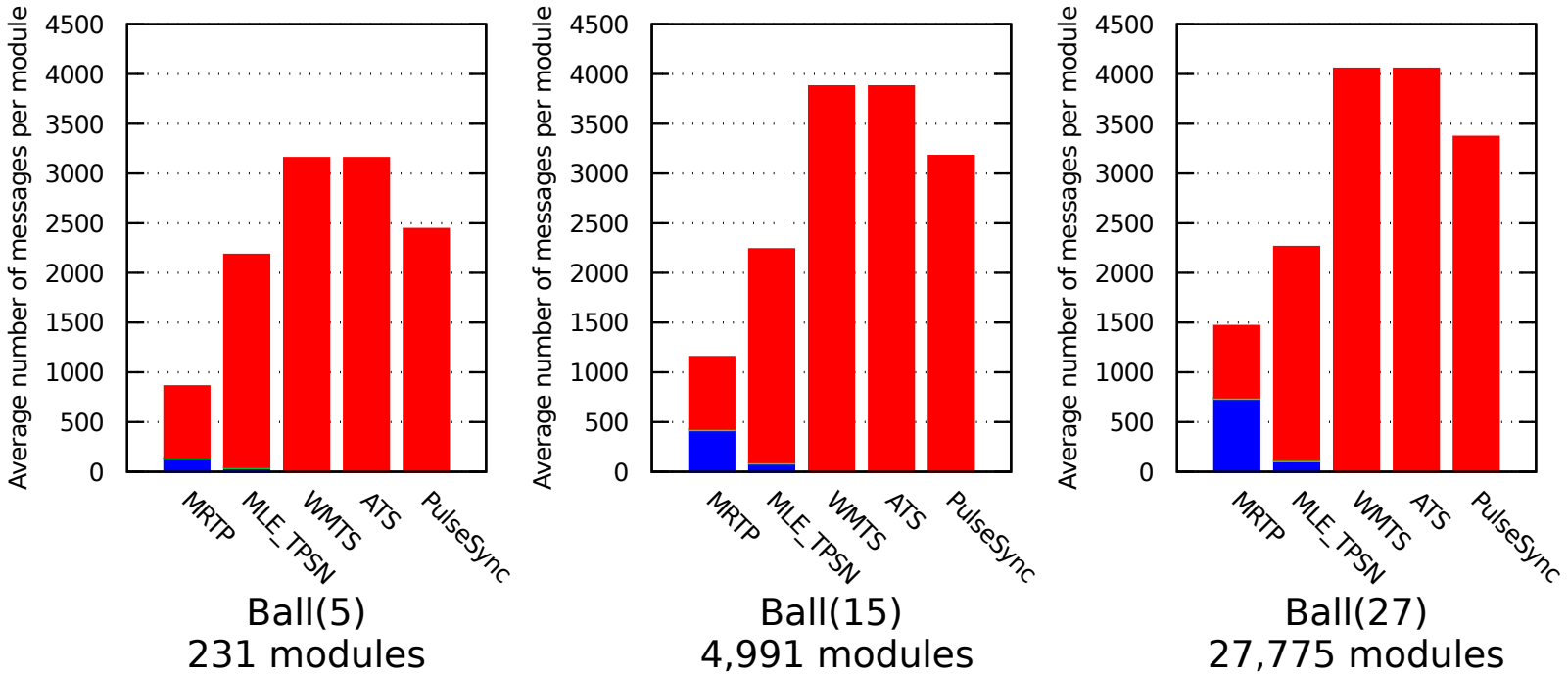




$\Longrightarrow$ MRTP is the most precise protocol

$\Longrightarrow$ MRTP synchronizes the 27,775 module system to 17ms in average

Messages



$\Longrightarrow$ MRTP uses few messages

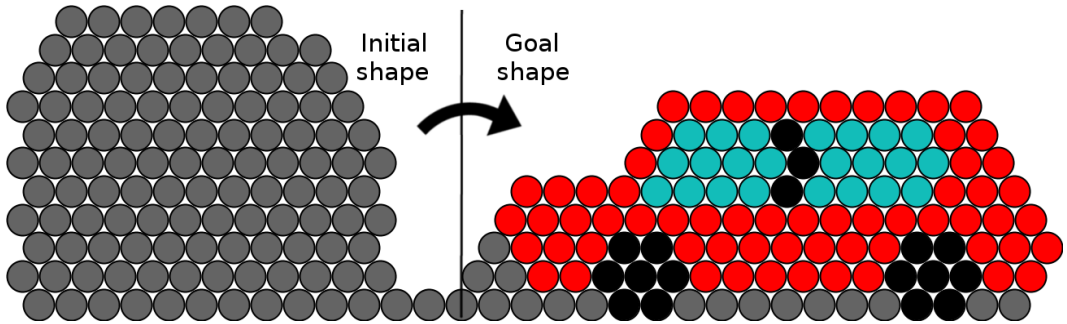
Conclusion

- The Modular Robot Time Protocol (MRTP)
- Evaluation
  - Hardware
  - Simulations
    - Most precise protocol with a fast convergence
    - Synchronizes a 27,775 module system with a 54-hop diameter to $< 20ms$
    - Uses less messages in compact systems than existing algorithms
- Limit
  - Targets fairly stable systems

Section Outline

Problem and Motivations

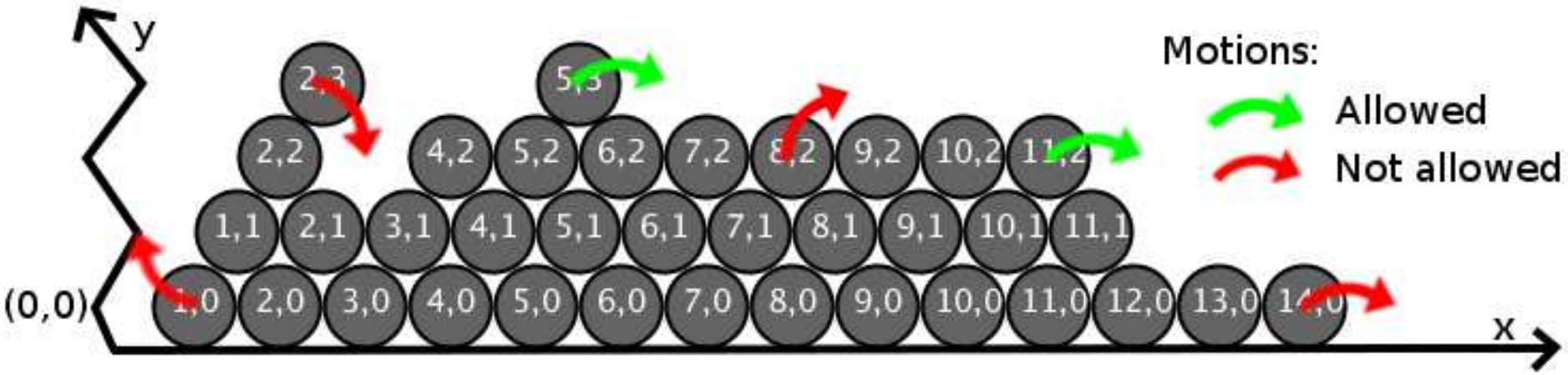
- Given an initial shape $\mathcal{I}$, a goal shape $\mathcal{G}$ and the mechanical constraints
- Problem: self-reconfigure the robot from shape $\mathcal{I}$ to $\mathcal{G}$



- Challenge: Distributed coordination
  - Effectiveness: reach $\mathcal{G}$
    - Prevent collisions
    - Prevent deadlock
  - Efficiency
    - Execution time
    - Motion
    - Communication
- Motivation: programmable matter

System Model and Assumptions

- Hexagonal lattice:
  - Every module knows its coordinates and its neighbor ones
- Communications:
  - Asynchronous
  - Neighbor-to-neighbor only
- Motions:
  - Asynchronous
  - Mechanical constraints
  - No presence sensor: prevent collisions using communications
- Failure-free environment (modules, communications, motions, lattice)
- Every module stores a complete representation of $\mathcal{G}$



Related Work

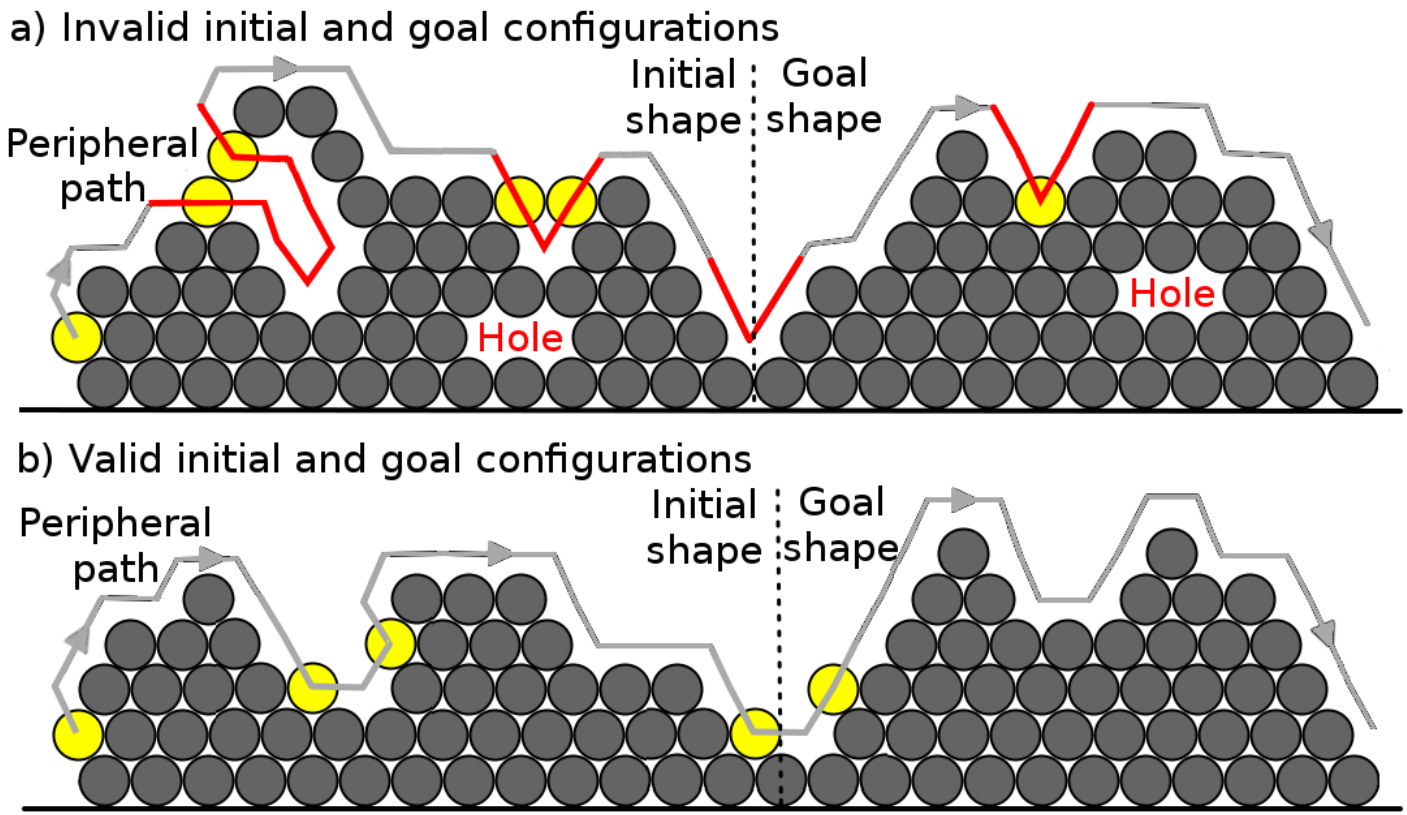
Cite	Shapes	Constraints on module movement	Collision and deadlock avoidance
[Walter et al., 2000]	chain to chain	relaxed	centralized pre-computation, synchronous rounds
[Walter et al., 2005, Bateau et al., 2012]	chain to 2D	relaxed	centralized pre-computation, synchronous rounds
[Lakhlef et al., 2015]	chain to square	relaxed and very-relaxed	predefined shape construction
[Lakhlef et al., 2014]	arbitrary to square	relaxed	predefined shape construction
[Wong et al., 2015]	compact 2D to chain	relaxed	touch sensors, synchronous rounds, single direction
[De Rosa et al., 2006]	2D	relaxed	
[Rubenstein et al., 2014]	horizontal 2D compact	very relaxed	collision allowed (swarm robotic)
Contribution: C2SR	vertical 2D compact	strong	messages, single direction

Subsection Outline

5 Self-Reconfiguration
- Problem and Motivations
- System Model and Assumptions
- Related Work
- Contribution: The Cylindrical-Catoms Self-Reconfiguration (C2SR) Algorithm
  - Shape Admissibility Conditions
  - Algorithm
- Evaluation
- Conclusion

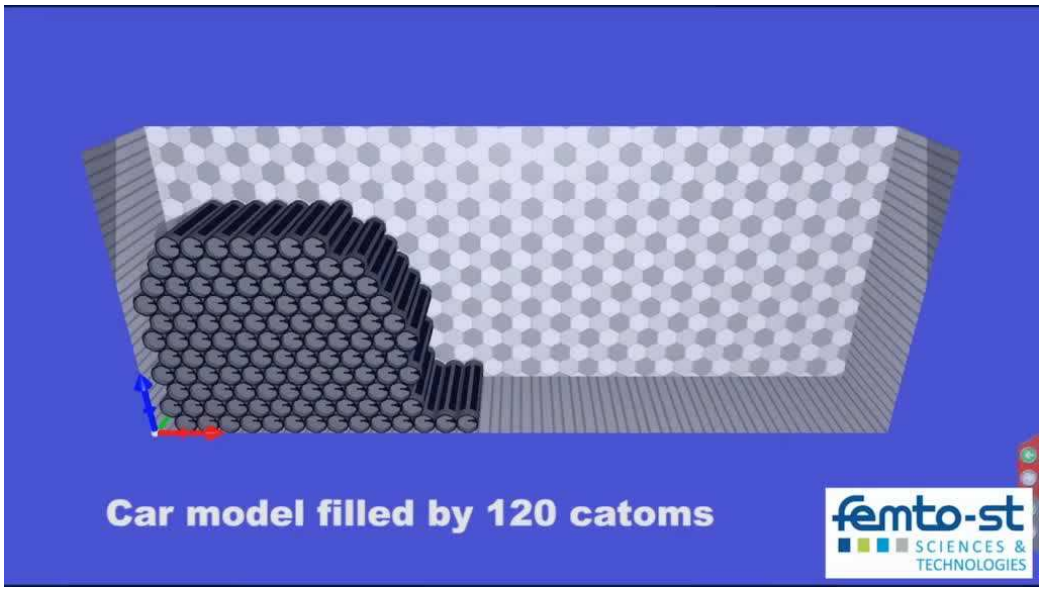
Shape Admissibility Conditions

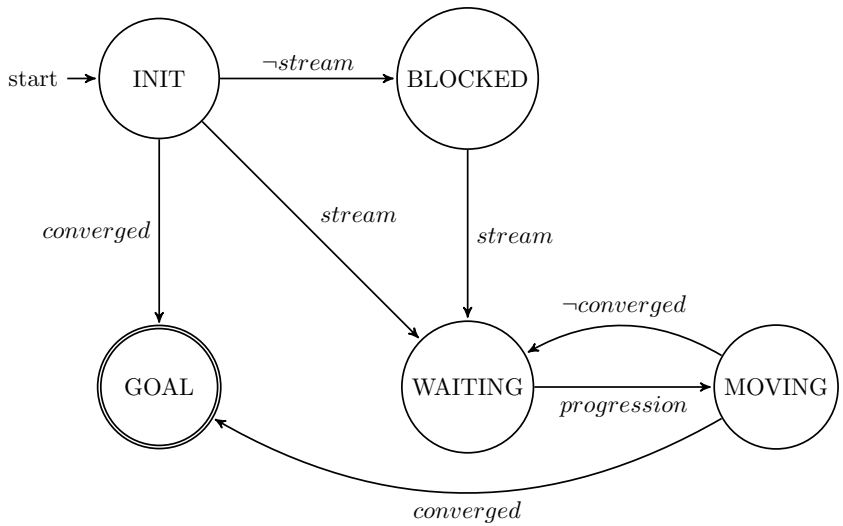
- $|\mathcal{I}| \geq |\mathcal{G}|$
- $\mathcal{I}$ and $\mathcal{G}$ are next to each other and share some bottom cells
- No hole
- Wide peripheral path with no narrow passage



C2SR at a Glance

- Stream of moving modules on the periphery
- Maintains an empty cell between moving modules
- Layer-by-layer deconstruction/construction (for shapes with only continuous horizontal layers)
- Decentralized with local interactions only (< 5 hops)
  - Communications with modules geographically around the next position in the stream

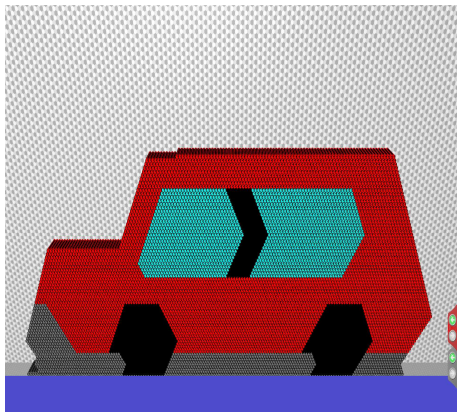


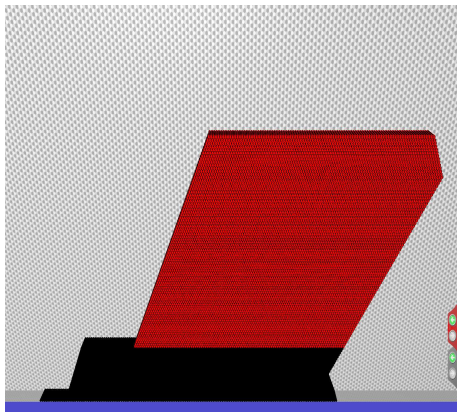


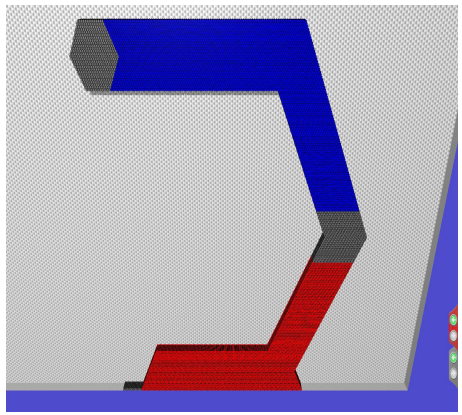
Subsection Outline

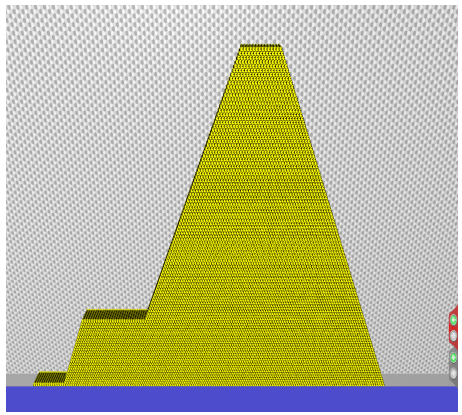
Experiment Setup

- VisibleSim
- Parameters (unless otherwise mentioned)
  - 4 shapes with different scale from 10^1 to 10^4 modules
  - Communication rate $\rightarrow \mathcal{N}(38.9kpbs, 389bps)$ $([3ms, 8ms])$
  - Motion speed $\rightarrow \mathcal{N}(1.88mm \cdot s^{-1}, 0.0188mm \cdot s^{-1})$ $([273ms, 285ms])$
- Evaluation criteria
  - Effectiveness
  - Efficiency
    - Time
    - Motion
    - Communication

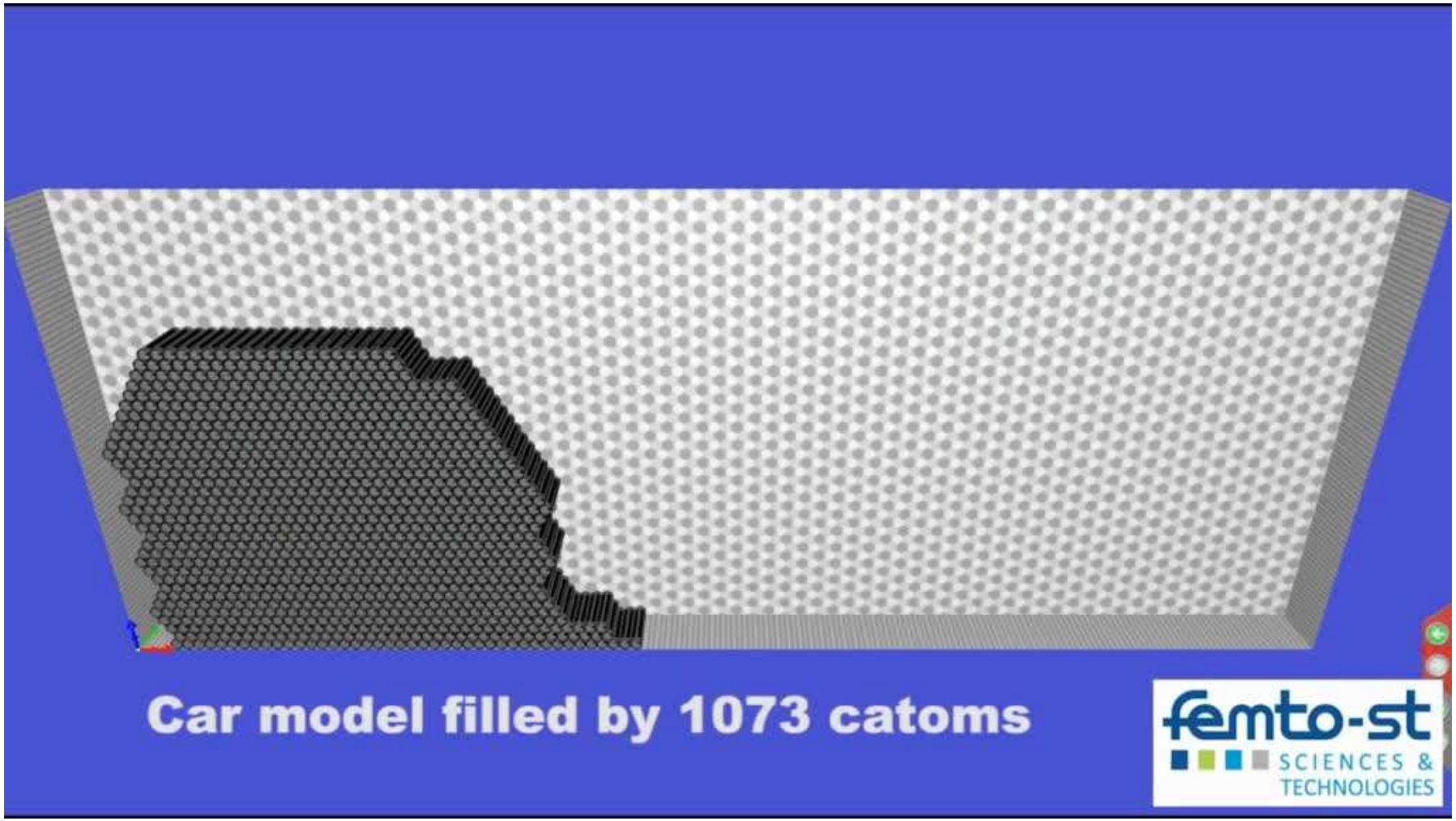

Car


Flag


Magnet

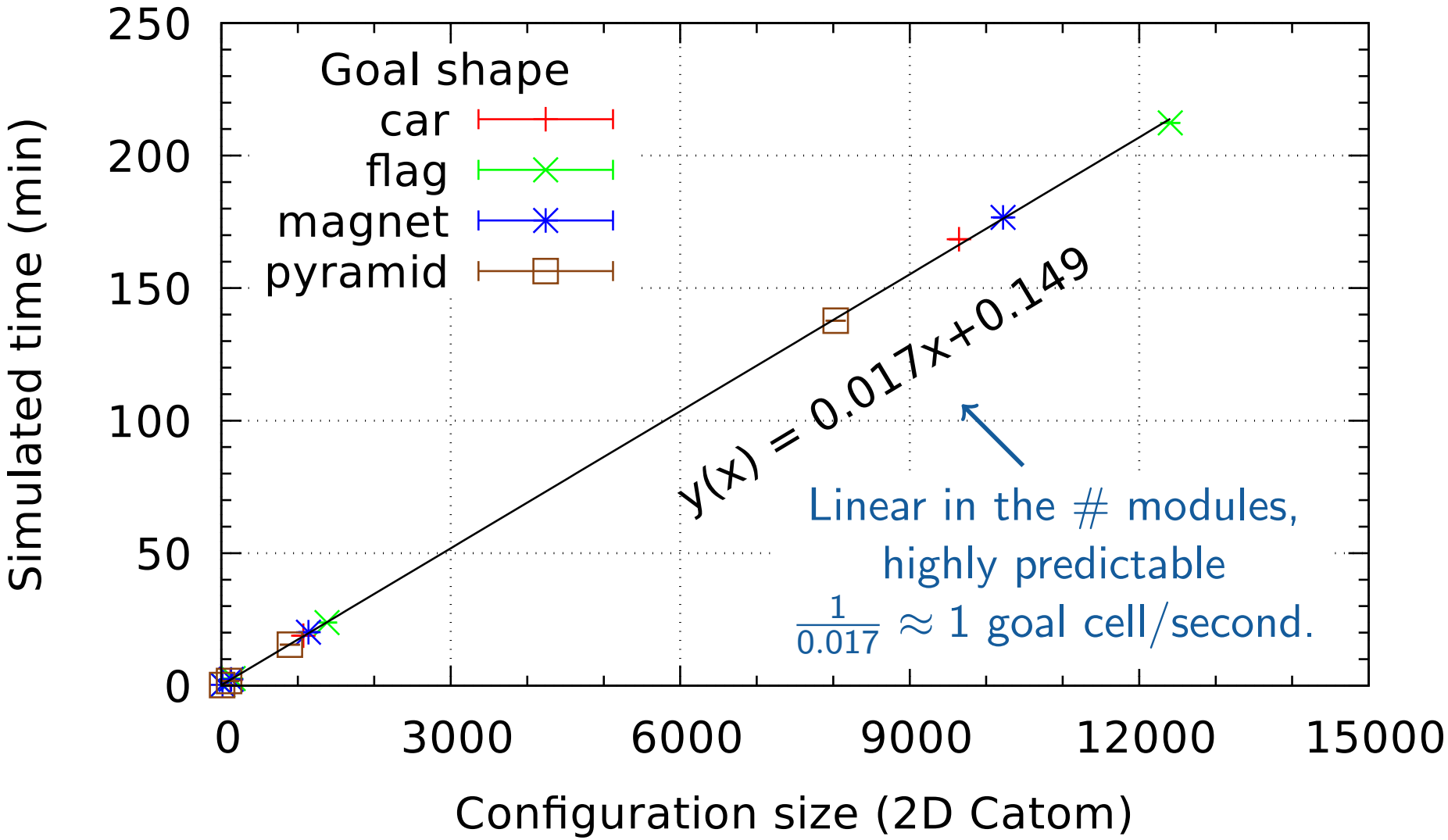

Pyramid

Effectiveness: C2SR in Video



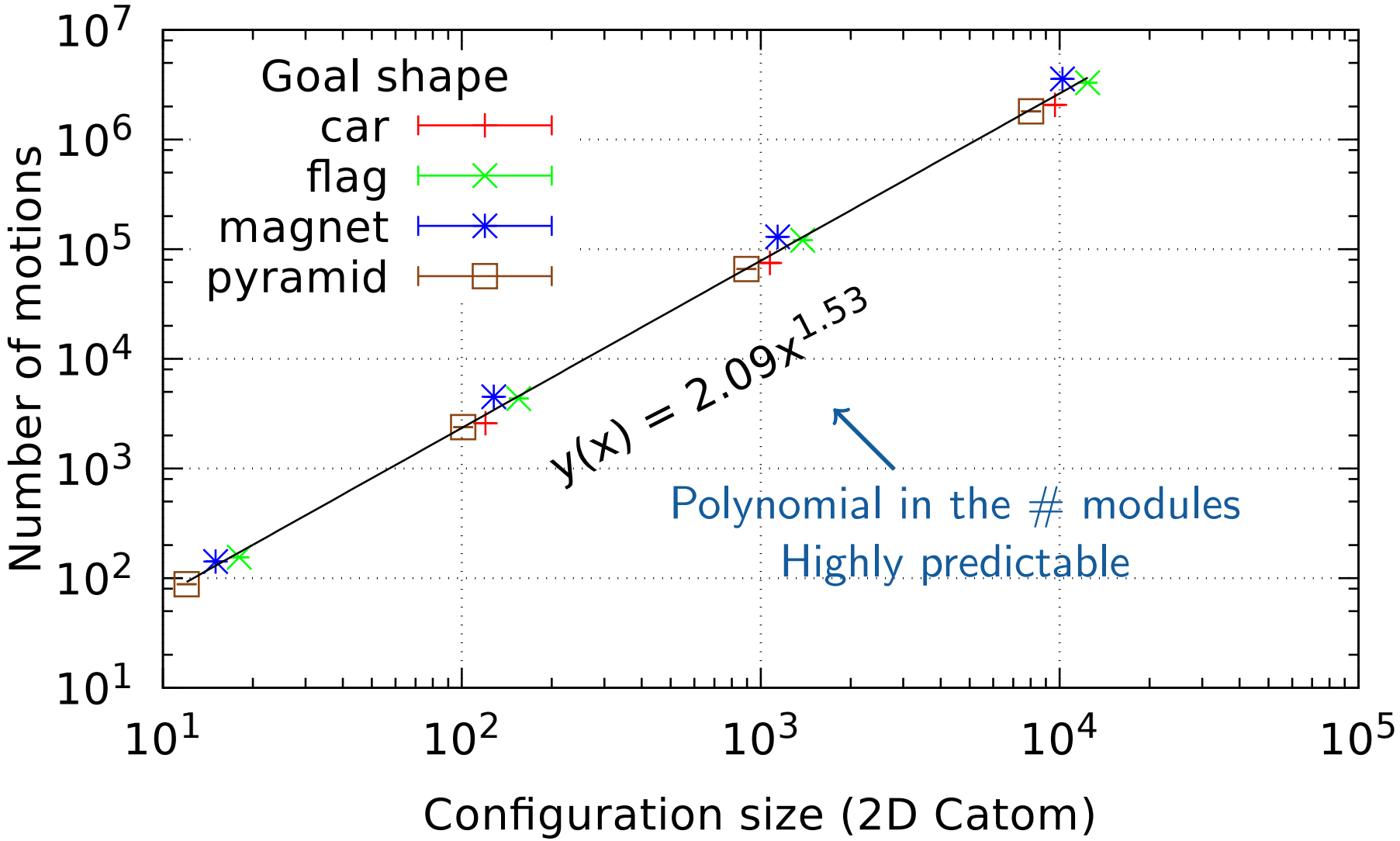
*Speed: x3

Execution Time ($\pm$ standard-deviation)



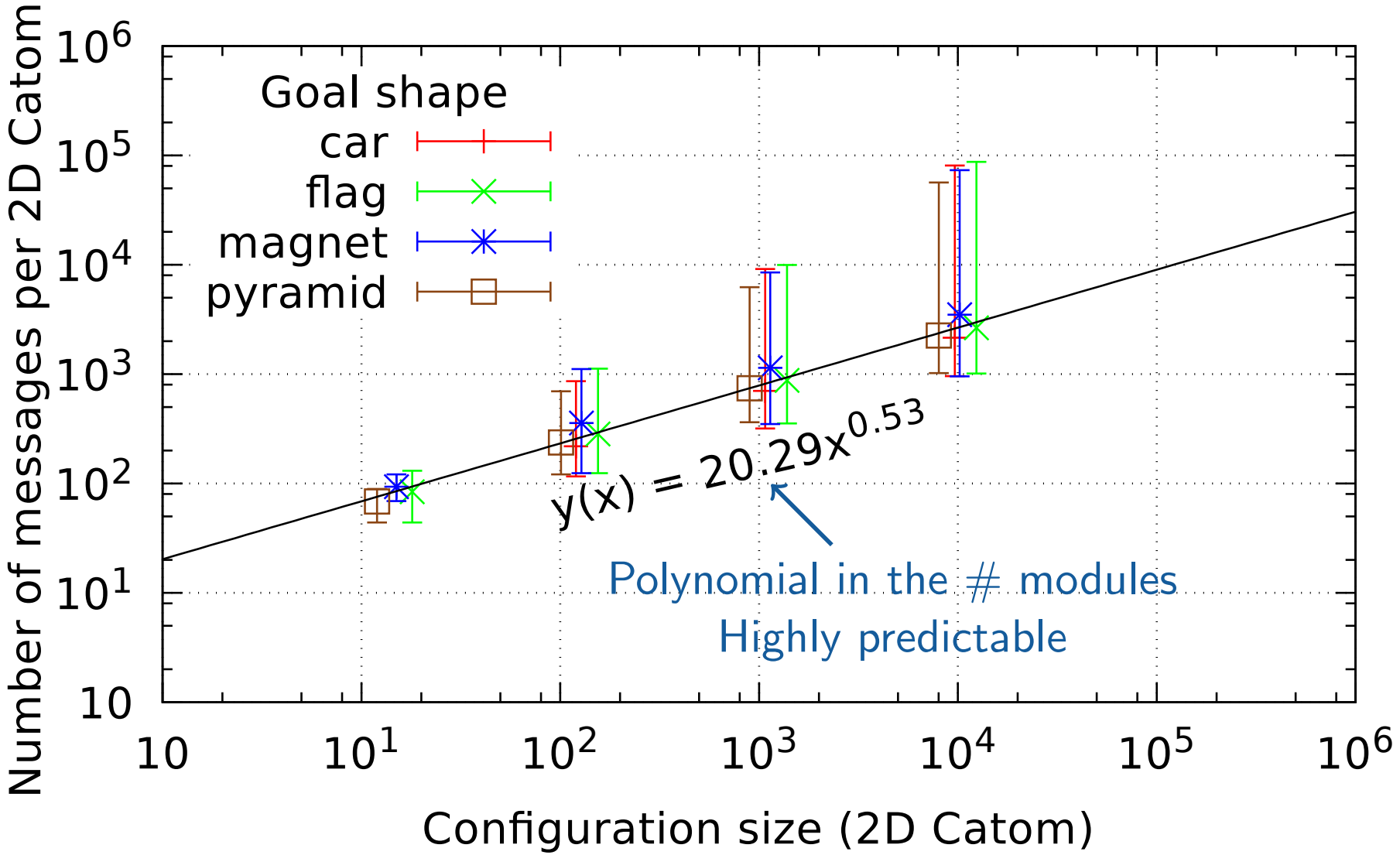
*Each point: 10 executions

Average Total Number of Motions (± standard-deviation)



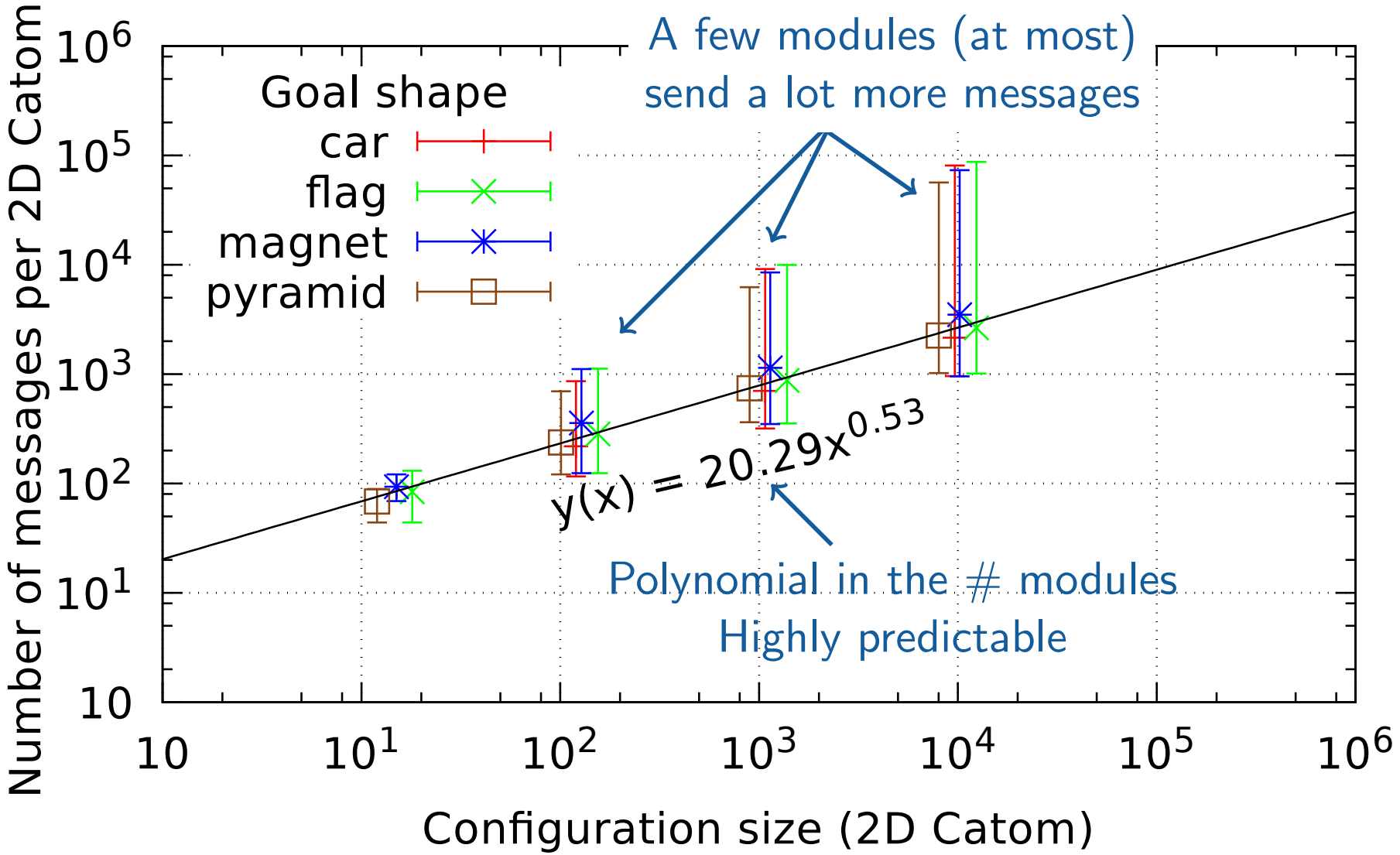
*Each point: 10 executions

Average Number of Messages per Catom (± min/max)



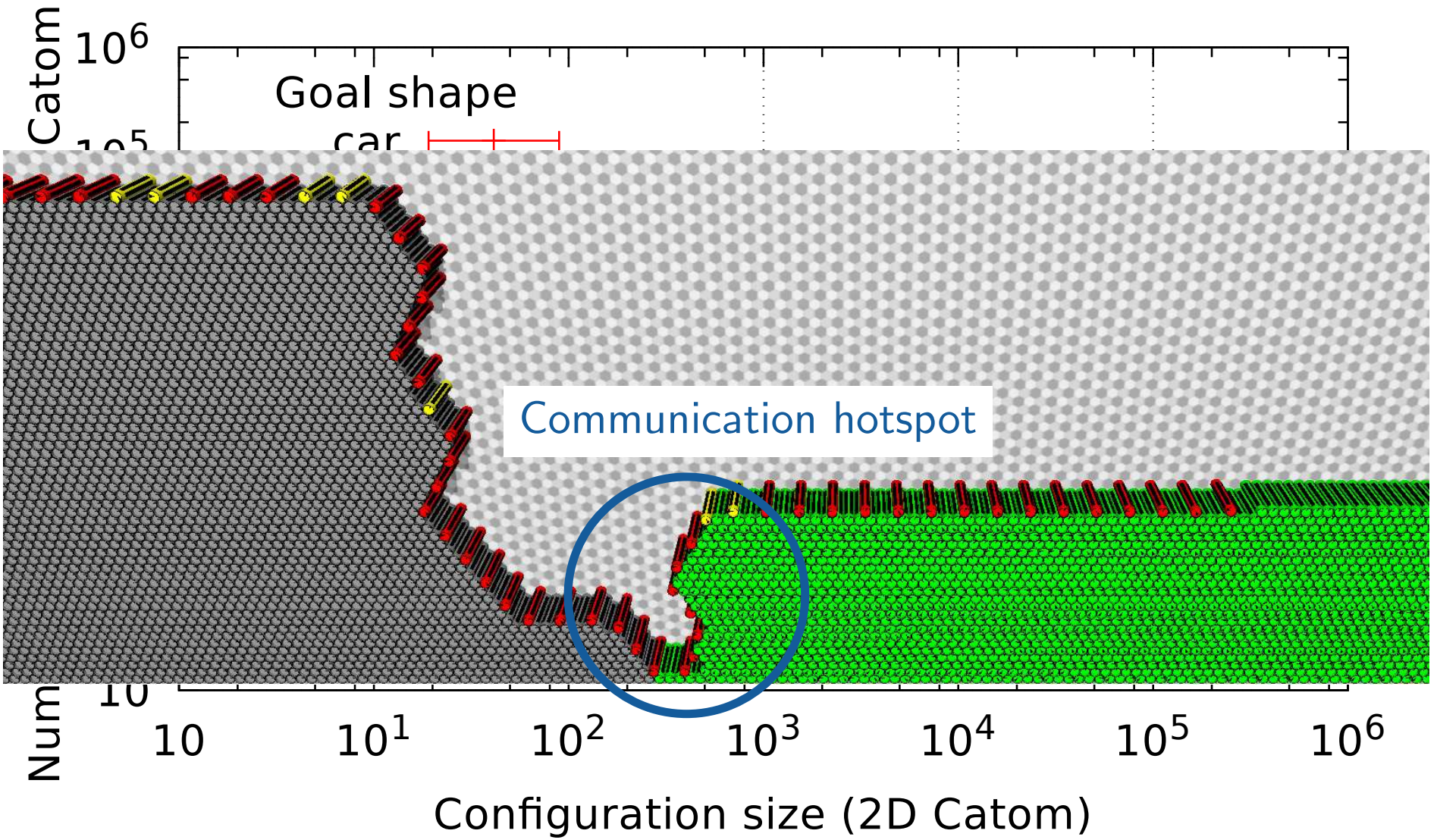
*Each point: 10 executions

Average Number of Messages per Catom (± min/max)



*Each point: 10 executions

Average Number of Messages per Catom (± min/max)



*Each point: 10 executions

Conclusion

- The Cylindrical-Catoms Self-Reconfiguration (C2SR) Algorithm
  - Effective: tested on different types of shapes
  - Scalable: tests with more than 10,000 modules
  - Nice properties:
    - Execution time seems linear in the size of the goal shape
    - Highly predictable: number of motions and messages
- Limits
  - Correctness and performance only shown experimentally
  - 2D systems only

Section Outline

Conclusion and Future Works (1)

- Contributions
  - Three efficient algorithms for distributed centrality-based leader election
  - The Modular Robot Time Protocol (MRTP)
  - The 2D-Catoms Self-Reconfiguration (C2SR) algorithm

- Future works
  - Centrality
    - Proofs on the accuracy of our algorithms
    - Deployment on other platforms with different network structures
    - More efficient management of network dynamics
  - Time synchronization
    - Deployment on ensembles with more precise clocks
    - Consider both clock stability and centrality to select the time master
    - Time synchronization in more dynamic ensembles
      - Synchronized self-reconfiguration?
      - For now, PulseSync [Lenzen et al., 2015] can be used

Conclusion and Future Works (2)

- Future works (cont'd)
  - Self-reconfiguration
    - Proof of correctness
    - Demonstration of the execution time linearity
    - Other models
      - Other mechanical constraints
      - 3D systems

Questions

Thank you for your attention!

Any question?

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