International Council on Systems Engineering
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MilliSwarm: Leveraging Emergence for Energy Efficient Robotic Swarm Movement

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INCOSE International Symposium 2025 | Ottawa, Canada

Guideline for this discussion

- What needs addressed and Why?
  - The Inspiration
  - Why should systems engineers care?
  - Background and Previous Works
- The Experiment
  - Simulation Environment
  - The Strategies
  - Experiment Setup
  - Results
- Conclusion

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The Inspiration: Nature's Odd Group Habits

Research Question: How does rolling swarm movement impact energy savings in swarm systems?

Rolling swarm behaviors are seen in a variety of myriapod species (Video sourced from Reddit)

Why should systems engineers care about millipedes?

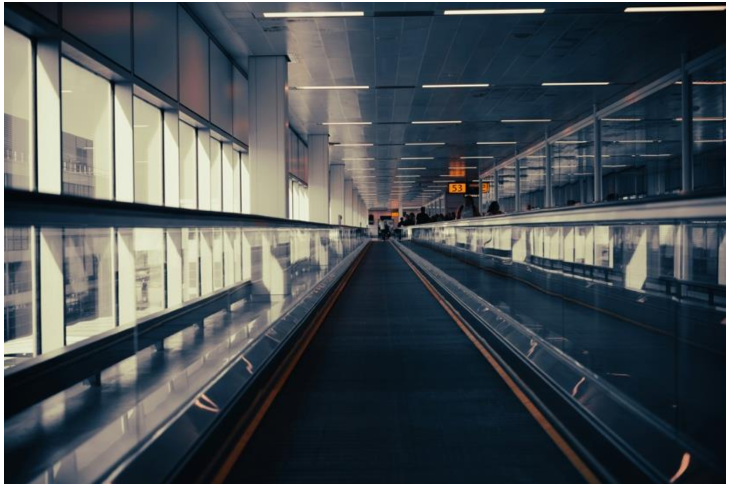
Biological systems and species provide a unique look at energy efficiency that has been culminating for millions of years in some species

Highlights a need for understanding complex systems and areas in which efficiency can be achieved

Myriapods have been on Earth for up to 425 million years by some estimates (Image from National Geographic: Elhardt 2017)

Context and Previous Works

Some previous explorations of this behavior focused on the speed of the swarm, rather than the energy used.



Airports, and even this conference center, have used moving platforms for speed and efficiency (Image sourced from Unsplash.com)

Some news/entertainment sources attempted limited speed analysis based on the Science and Engineering YouTube channel: Smarter Every Day (GIF sourced from Wired.com)

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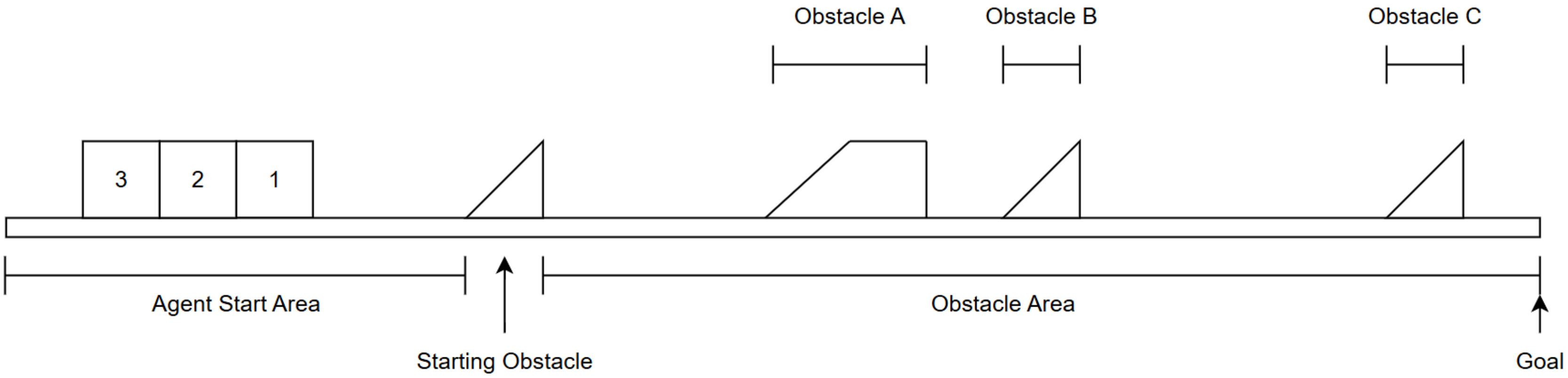
The Experiment: The Simulation Environment

To simplify the experiment and focus on an energy savings approach agents are modeled as sliding blocks



The Experiment: The Strategies - Control

Two different approaches were considered for this experiment, as well as a control group

The Experiment: The Strategies – Leg Up

This strategy focused on simply helping other agents over an obstacle for a lower cost than climbing

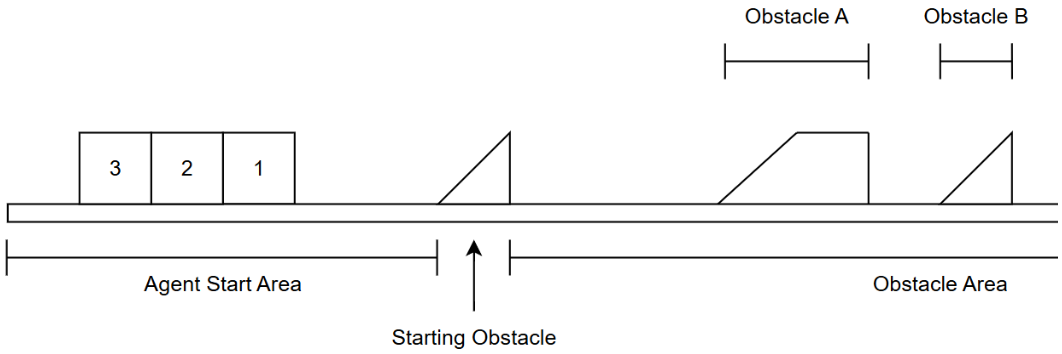
The Experiment: The Strategies – MilliSwarm

This strategy combined helping other agents over an obstacle with the identified millipede rolling swarm behaviors

The Experiment: The Math

Using the sliding block model for the agents simplifies the energy costs for agents to do things

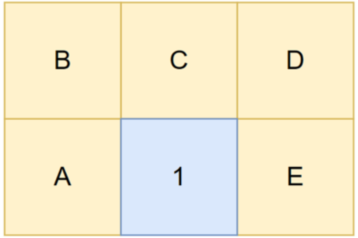
- Total Agent Energy Cost: $\boldsymbol{F_{tot}} = \boldsymbol{F_g} + \boldsymbol{F_N} + \boldsymbol{F_m} + \boldsymbol{F_{sf}}$
- Force of Gravity: $\boldsymbol{F_g} = m * g * \sin(\theta)$
- Normal Force: $\boldsymbol{F_N} = m * g * \cos(\theta)$
- Sliding Force: $\boldsymbol{F_{sf}} = \mu * N = \mu * m * g * \cos(\theta)$
- Movement Force: $\boldsymbol{F_m} = F_g + F_N + F_{sf}$
  - $\boldsymbol{F_m} = m * g * \sin(\theta) + \mu * m * g * \cos(\theta)$
- Cost to Climb: $\boldsymbol{\Delta PE} = m * g * h$



The Experiment: Setup and Variables

Using the equations from the previous section these ranges were used for the three trial types within this experimental setup

- Agent Characteristics
  - 10cm by 10cm aluminum squares
  - 1kg in mass



Where Agent 1 can sense position data from

	Baseline (Joules)
Climb an Obstacle (Obstacle)	1.4404
Climb onto an Agent (Climb)	.98
Move on a flat surface (Base)	.4606
Move while on an agent (Top)	.392
Move with an agent above (Bottom)	.9212

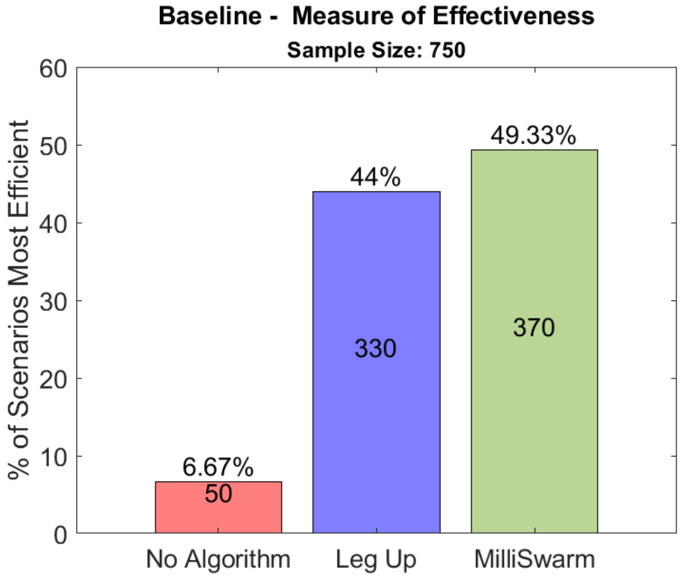
	Baseline
Number of Agents	1 - 15
Number of Obstacles	1 - 50
Distance to Goal	150 centimeters

Test 1: Baseline Values

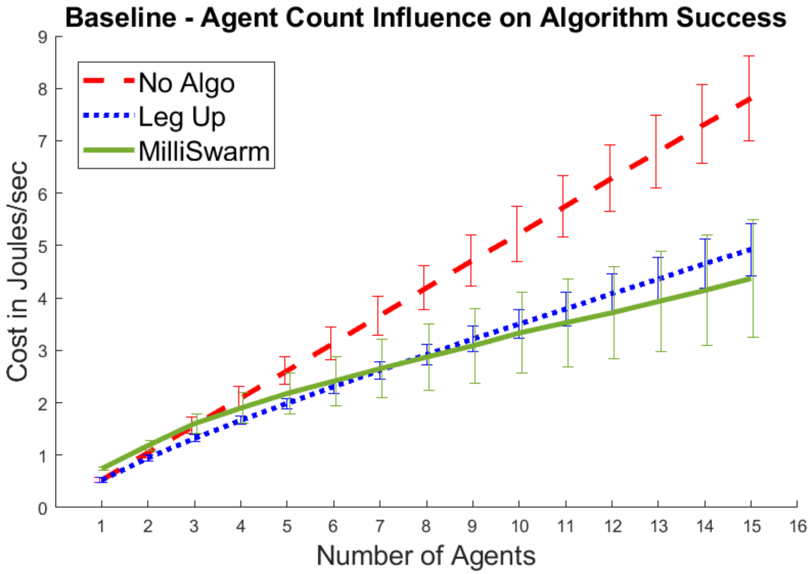
Cost for actions are based on the costs presented previously as Baseline

The Results: Basic Model

In a slim majority of scenarios the MilliSwarm algorithm provides the more efficient solution



750 Samples are based on the unique number of combinations of agent (1-15) and obstacle (1-50) counts



Test 2: Variable Cost

Cost for actions are based on a uniform distribution, based around ± 25% of Baseline values

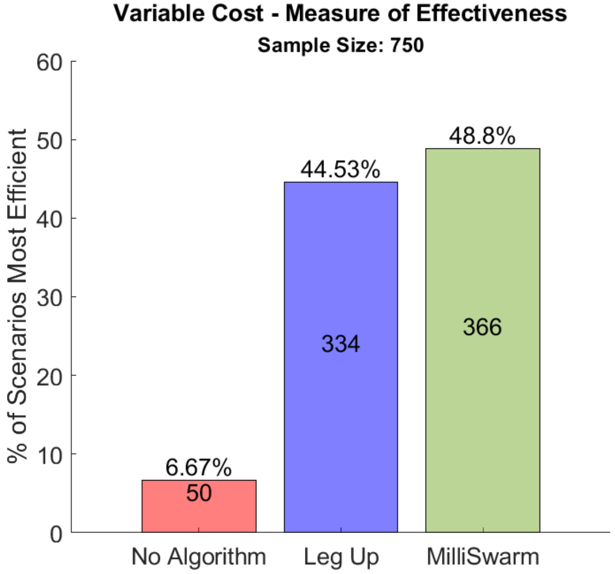
The Results: Impact of Variable Cost

This test was done to ascertain the impact of different variable costs, and to challenge the assumptions made in the Baseline model

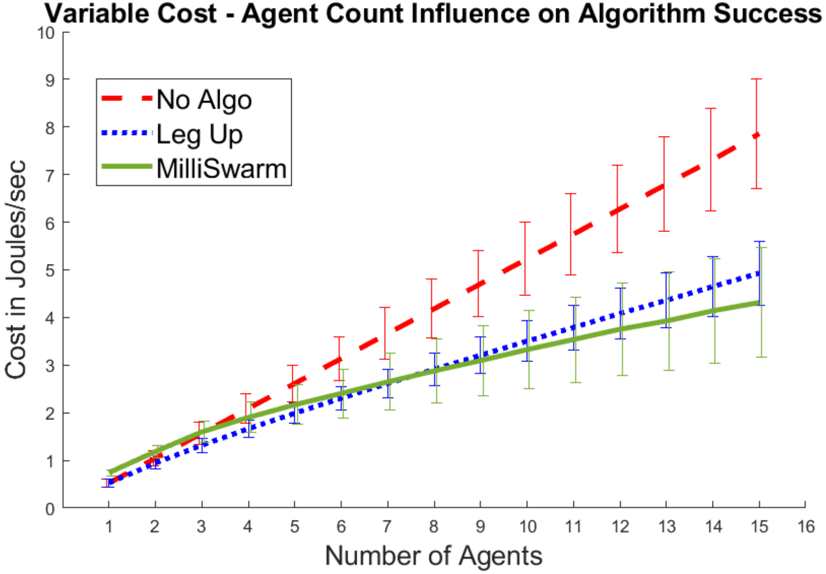
	Min Val (J)	Max Value (J)	Bin Size	Total Bins
Climb an Obstacle (Obstacle)	1.083	1.797	.001	721
Climb onto an Agent (Climb)	.735	1.225	.001	491
Move on a flat surface (Base)	.345	.576	.001	232
Move while on an agent (Top)	.294	.49	.001	197
Move with an agent above (Bottom)	.691	1.51	.001	461

The Results: Impact of Variable Cost

When looking at this data with a “agent and obstacle” lens the results seem nearly identical to the base model

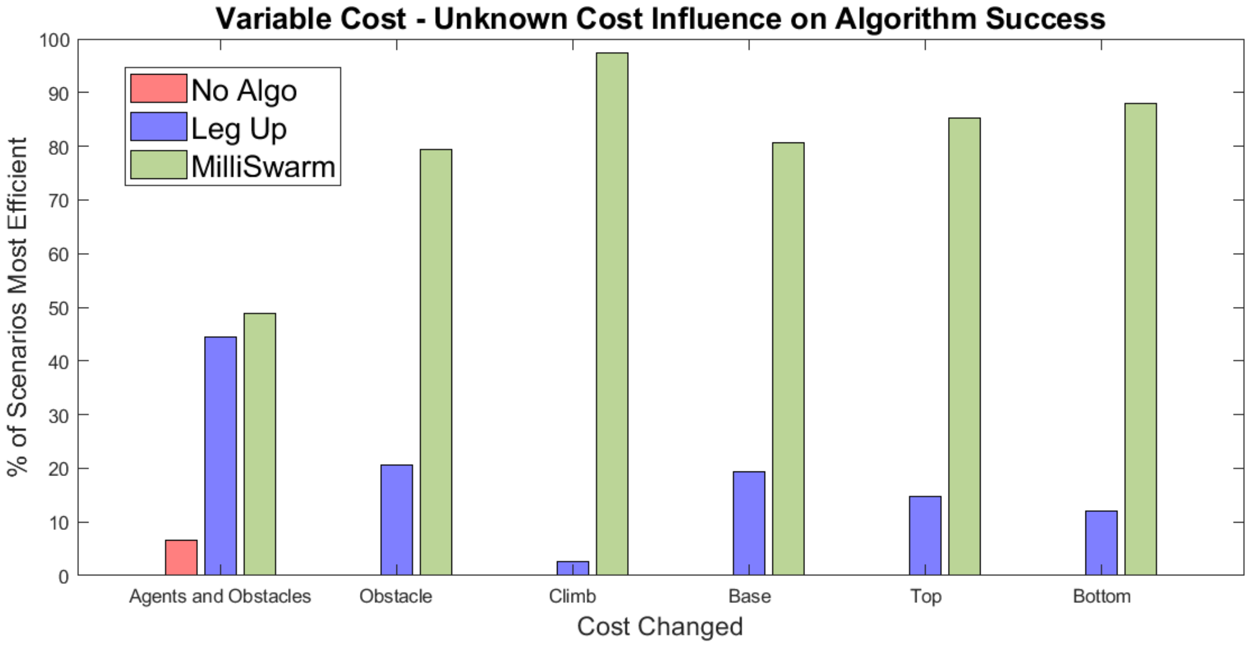


Again, the 750 Samples are based on the unique number of combinations of agent (1-15) and obstacle (1-50) counts, not unique variable cost combinations



The Results: Impact of Variable Cost

In almost all scenarios the MilliSwarm algorithm is the premier choice when you know little about your test environment and costs

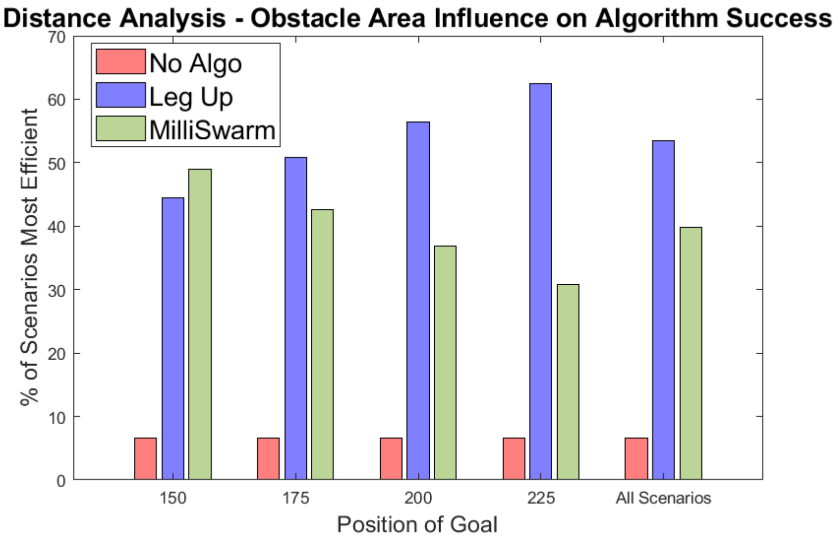


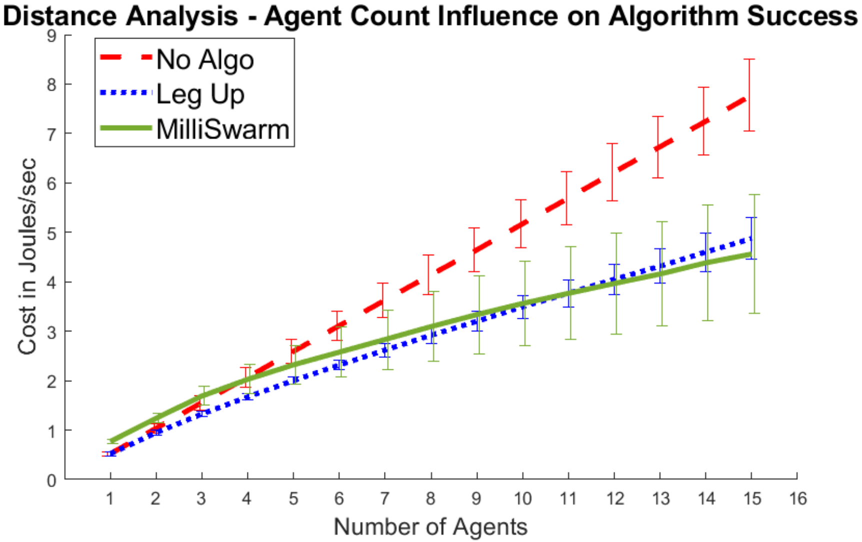
Test 3: Distance

Cost for actions are Baseline values, but with changes in the default 150 centimeter goal distance

The Results: Impact of Distance

As distance increases the mean improvement from MilliSwarm decreases when compared to only helping others over obstacles





The Results: All Data Sets

	MilliSwarm (J/s)	Improvement over Control	Improvement over Leg Up
Baseline Data	2.7729	33.58323%	2.701849%
Variable Cost – All Data	2.7775	33.71754%	2.786042%
Variable Cost – Obstacle Data	2.7772	33.71521%	2.782931%
Variable Cost – Climb Data	2.7778	33.71988%	2.785749%
Variable Cost – Base Data	2.7774	33.74523%	2.816754%
Variable Cost – Top Data	2.7773	33.73181%	2.796444%
Variable Cost – Bottom Data	2.7776	33.71674%	2.785944%
Distance Analysis – All Data	2.9441	28.68839%	-3.93631%
Distance Analysis – 150 Goal	2.7532	33.51686%	2.724093%
Distance Analysis – 175 Goal	2.8912	30.35938%	-2.0904%
Distance Analysis – 200 Goal	3.0089	27.01273%	-6.32907%
Distance Analysis – 225 Goal	3.1229	23.80569%	-10.0271%

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Conclusion and Final Remarks

- MilliSwarm provides a measurable increase in energy efficiency over control groups.
- Recent work by other groups have begun developing robot systems similar to millipedes and centipedes, opening the door to implementation of these biological behaviors.

Multilegged robot from Ground Control Robotics (Image from IEEE Spectrum, 2025)

Questions?

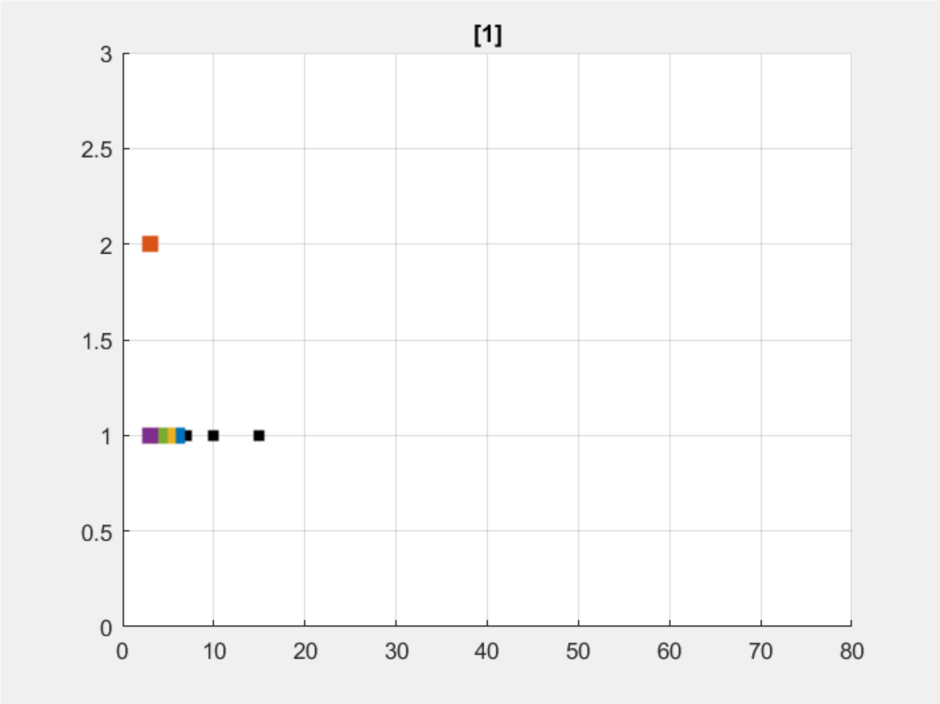
Average for All Random Cost and Number of Obstacles (50,000 Trials)

	Time	Cost (J)	J/s	Improvement over Control
No Algorithm (Control)	148	670.1752	4.528211	0%
Leg Up	198.5859	645.36.33	3.098836	31.56%
MilliSwarm	180.0156	559.9893	3.027543	33.14%

Supporting Slides

The Experiment: MilliSwarm

A visual example of what MilliSwarm looks like in motion



The Results: All Data Sets

	No Algorithm Mean Joules/Sec	Leg Up Mean Joules/Sec	MilliSwarm Mean Joules/Sec	Most Efficient Choice
Baseline Data	4.1750	2.8499	2.7729	MilliSwarm
Variable Cost – All Data	4.1904	2.8571	2.7775	MilliSwarm
Variable Cost – Obstacle Data	4.1898	2.8567	2.7772	MilliSwarm
Variable Cost – Climb Data	4.1910	2.8574	2.7778	MilliSwarm
Variable Cost – Base Data	4.1920	2.8579	2.7774	MilliSwarm
Variable Cost – Top Data	4.1910	2.8572	2.7773	MilliSwarm
Variable Cost – Bottom Data	4.1905	2.8572	2.7776	MilliSwarm
Distance Analysis – All Data	4.1285	2.8326	2.9441	Leg Up
Distance Analysis – 150 Goal	4.1412	2.8303	2.7532	MilliSwarm
Distance Analysis – 175 Goal	4.1516	2.8320	2.8912	Leg Up
Distance Analysis – 200 Goal	4.1225	2.8298	3.0089	Leg Up
Distance Analysis – 225 Goal	4.0986	2.8383	3.1229	Leg Up