

Contents

Abstract	vii
Acknowledgments	xiii
Contents	xvi
1 Introduction	1
2 State of the art	9
2.1 Swarm robotics	10
2.2 Design	12
2.2.1 Manual design	12
2.2.2 Automatic design	18
2.3 Collective behaviors	21
2.3.1 Spatially-organizing behaviors	21
2.3.2 Navigation behaviors	26
2.3.3 Interaction with humans	28
2.4 Notable robot swarms	29
2.5 Cognition	31
2.5.1 Cognition and planning in robotics	34
2.5.2 Cognition in swarm robotics	40
3 TS-Swarm Mark I	47
3.1 Distributed task-sequencing algorithm	48
3.2 Platforms	50
3.2.1 The e-puck	51
3.2.2 The TAM	52
3.2.3 ARGoS	53
3.3 Description of Mark I _m	53
3.4 Experiments with Mark I	70

3.4.1	Experimental design	70
3.4.2	Robot experiments	72
3.4.3	Assessment of the simulator	74
3.4.4	Scalability study	74
3.4.5	Robustness study	75
3.4.6	Experiments with Mark I ₄	78
3.5	Limitations and possible improvements	81
4	TS-Swarm Mark II	85
4.1	Description of Mark II	85
4.1.1	Mark II ₃	86
4.1.2	Mark II ₄	91
4.2	Experiments with Mark II	91
4.2.1	Experimental design	91
4.2.2	Experiments with Mark II ₃	92
4.2.3	Experiments with Mark II ₄	95
4.3	Possible improvements	98
5	Conclusions	101
A	Appendix	105
A.1	Introduction	105
A.2	E-puck	106
A.2.1	E-puck firmware architecture	106
A.2.2	E-puck in ARGoS	108
A.3	Range and bearing	111
A.3.1	Range and bearing firmware	111
A.3.2	Range and bearing in ARGoS	112
A.4	TAM	115
A.4.1	TAM architecture	115
A.4.2	TAM in ARGoS	117
	Bibliography	120

List of Figures

1.1	Example of mission that requires sequencing tasks. Image from Garattoni and Birattari (2018)	4
1.2	Simple robots form a chain gang to solve complex problems. Still from the video produced and published by Science	6
2.1	Virtual physics-based design.	15
2.2	Notable robot swarms. (A) Swarm-bot – Previously unreleased photo. Copyright: Marco Dorigo. (B) Swarmanoid – Still from the video: <i>Swarmanoid, movie</i> . Copyright: Mauro Birattari <i>et al.</i> Reprinted by permission. (C) TERMES – Still from the video: <i>Designing collective behavior in a termite-inspired robotic construction team</i> . Copyright: Justin Werfel <i>et al.</i> Reprinted by permission. (D) Thousand-robot Swarm – Still from the video: <i>Programmable self-assembly in a thousand-robot swarm</i> . Copyright: Michael Rubenstein <i>et al.</i> Reprinted by permission. (E) CoCoRo – Still from the video: <i>TYOC#52/52: Final Demonstrator</i> . Copyright: Thomas Schmickl <i>et al.</i> Reprinted by permission. (F) BioMachines Lab’s Aquatic Robot Swarm – Still from the video” <i>A Sea of Robots</i> . Copyright: BioMachines Lab. Reprinted by permission.	32
2.3	Hybrid system architecture for single robot.	38
2.4	Hybrid system architecture for multi-robot systems with a central planner.	39
2.5	Hybrid system architecture for multi-robot systems with distributed planner.	39
3.1	From task-sequencing missions to TS-Swarm. Image from Garattoni and Birattari (2018).	48
3.2	State machine of TS-Swarm.	54
3.3	Encoding of the range-and-bearing message in Mark I_m.	55

3.4	Guardians.	56
3.5	State machine of a guardian.	57
3.6	Guardian protocol (G protocol), sequence diagram.	58
3.7	Motion of a link.	60
3.8	Tail.	62
3.9	Tail protocol (T protocol), sequence diagram.	63
3.10	Construction and motion of a branch of chain.	66
3.11	Runners.	67
3.12	Trajectory followed by the runners around the chain.	68
3.13	Motion of a runner along a branch of the chain.	69
3.14	Experimental setting.	72
3.15	Overhead snapshots of robot experiments. Images from Garattoni and Birattari (2018)	75
3.16	Overhead snapshots, Mark I_m in simulation. Images from Garattoni and Birattari (2018)	76
3.17	Empirical assessments of Mark I_3.	77
3.18	Scalability and robustness analysis, the arenas. Image from Garattoni and Birattari (2018)	78
3.19	Scalability and robustness of Mark I_3.	79
3.20	Number of chain members in Mark I_3.	80
3.21	Empirical assessment of Mark I_4.	80
3.22	Scalability and robustness of Mark I_4.	82
4.1	The chain in Mark II_3 and Mark II_4.	87
4.2	Exploration of the space of possible sequences in Mark II_3.	88
4.3	Exploration of the sequence space in Mark II_3, as seen by the guardian of the green task. Image from Garattoni and Birattari (2018)	88
4.4	Encoding of the range-and-bearing message in Mark II_3.	90
4.5	Exploration of the space of possible sequences in Mark II_4.	91
4.6	Overhead snapshots, Mark II_m in simulation. Images from Garattoni and Birattari (2018)	93
4.7	Empirical assessment of Mark II.	94
4.8	Scalability and robustness of Mark II_3.	96
4.9	Comparison between Mark II_3 (blue) and Mark II_4 (red).	97
4.10	Comparison between Mark II_3 and Mark II_4.	97
4.11	Scalability and robustness of Mark II_4.	99

A.1	E-puck extended with range and bearing, Linux extension board and omni-directional camera.	107
A.2	Steps of a cycle of control of the e-puck software architecture.	108
A.3	The architecture of the real e-puck package integrated in AR-GoS.. Image inspired by Pinciroli et al. (2012)	109
A.4	The architecture of the e-puck simulation package. Image inspired by Pinciroli et al. (2012)	110
A.5	Measurements for calculation of noise on range perceived. . . .	115
A.6	Conceptual and real TAM. Image in A from Brutschy et al. (2015), image in B from Garattoni and Birattari (2018)	116
A.7	TAM software architecture.	118