Genetic Algorithm Applied to Robotic Squad Coordination

Gustavo Pessin, Fernando Osório, Denis F. Wolf and Maurício A. Dias
Institute of Mathematics and Computer Science (ICMC)
University of São Paulo (USP)
Av. do Trabalhador São-Carlense, 400 – C.P. 668 – 13.560-970 – São Carlos, SP, Brazil
{pessin,fosorio,denis,macdias}@icmc.usp.br

***Abstract*—The main goal of this paper is to describe the modeling, implementation and evaluation of the Genetic Algorithm's (GA) efficiency when applied to robotic group formation and coordination. The robotic task in this paper is performed over a natural disaster, simulated as a forest fire; the simulator is detailed in [1]. The robot squad mission is to surround the fire and avoid fire's propagation. Experiments have been made with different chromosome models and several parameter's variation. This paper describes all performed experiments detailing all sets of parameters, including positive and negative results. The simulation's results[1] showed that with an adequate set of parameters is possible to get satisfactory strategic positions for a multi-robotic system's operation; furthermore, this GA solution can be applied on similar activities.**

***Keywords*-Genetic Algorithm; Robotics; Coordination**

I. Introduction

The continuous evolution provided by mobile robotics research area has made even more efficient robots for several functions. Research about controlling complex motor functions are developed on several research centers around the world, encompassing studies about sensors and actuators, positioning, navigation and localization in addiction to many other requirements related to robotic hardware, as demonstrated by [2], [3], [4]. Specialized algorithm development composed by rule based systems and automats have been developed in order to coordinate these physical sets in a dynamic environment. This is an extremely complex challenge [5]. Giving to autonomous mobile robots the ability of intelligent reasoning and ways to interact with the environment is a research challenge which has attracted the attention of a great number of researchers [2].

One of the primary goals of robotic systems usage is that they can help in tasks extremely dangerous to human beings, like cleaning nuclear residuals, cleaning chemical accidents, forest fire combat or even on constructions, agriculture, hostile environment exploration, security and critical missions. There are many fields where a single robotic agent is insufficient or inefficient to complete a task, and in several activities the better idea is to use multi-robotic systems. Multi-robotic systems are systems where autonomous mobile robots work cooperatively to complete a mission with robots interaction or not [6]. These systems are extremely dependent on control techniques. Related to the applicability, multi-robotic systems can add mobility, flexibility and robustness of a new way to a wide range of new applications [7].

In [8] we proposed a simulation environment for recognition and combat of forest fire with rule based agents. In [9] we presented an evolution of the virtual environment, using the physical simulation library Open Dynamics Engine (ODE) [10], where new artificial intelligence techniques where applied on the agents. This present work's goal is to describe experiences with genetic algorithms doing a searching for optimal acting (strategic) positions in a multi-robotic system. The GA evaluation is made considering a robotic task performed over a natural disaster, simulated as a forest fire propagation. Experiences with two and four firefighter robots where made.

In section 2 of this paper mobile robotics concepts and applications are presented. In section 3 some Genetic Algorithm applications and related concepts are presented. Section 4 describes the simulator, the proposed fitness and the chromosome, concluding with detailed description of results and experiments.

II. Mobile robotics

The problem-solving task capabilities of multi-robotics system depend on higher developed capacities of each single robot; they can count including with different robots capacities (such as heterogeneous systems). Several current works demonstrates mobile robotic usage (individual system) on hostile operations as the rescue auxiliary robot Raposa [11] and SACI robot [12] designed for acting on fire combat. The militaries prototypes Boeing X-45 [13] and nEUROn [14] that, under human-landed supervising (without embedded pilot) are being tested for combat missions. Moreover, there are robots to perform tasks on aquatic environments, to space, caves and volcanoes exploration, and even to household use. There are also competitions [15], [16] that uses small autonomous mobile robots that have missions like find and put out a candle (as a simulated fire).

Multi-robotic systems must be formed by robots that are able to effective acting on tasks, so knowledge about robotic control is a very important field. Works describing

[1]Souce-code and videos availables at http://pessin.googlepages.com

978-0-7695-3799-3/09 $26.00 © 2009 IEEE
DOI 10.1109/CERMA.2009.17

intelligent robot navigation can be seen in [17], [18], [19]. In 2004 and 2005, DARPA Grand Challenge [20], financed by the Defense Advanced Research Projects Agency organized a competition where the goal was building a completely autonomous vehicle that can complete a long way on dirt road on limited time. In 2007 the focus of the competition has changed. Renamed to DARPA Urban Challenge, had a new goal to build a vehicle that can be autonomous on urban traffic, and realize tasks like parking, overtaking and intersection negotiations. These examples show trends in cooperation and multiple interactions.

The main motivation on multi-robotic systems usage is that they add extra capacity on solving problems. The work with groups adds a great number of possibilities on tasking-solving but bring a series of new questions to be solved in collaboration and cooperation. Works using multi-robotic systems like [21], [22] uses pre-programmed rules on agents to perform formation. In [7], [23] are explored techniques to perform works with collectives robotics, used mainly for the purpose of applying the concept of self-organization and collective optimization, but task division is not directed explored. The works described demonstrate that the application of mobile robotics in control of incidents is an important and active topic of research and development. These several competitions also demonstrate that there isn't a definitive or more adequate solution to the problem, and it's an open research field. In all consulted documents there's no consensual form to multi-robotic system's conformation and actuation. Unpredicted situations with large degree of autonomy and robustness are still difficult to handle.

III. Genetic algorithms

Genetic Algorithms [24], [25] are global optimization techniques that use parallel and structured search strategy [26]. It allows multi-criteria search on a multi-dimensional space. These techniques are classified as non-supervised because they don't need any initial information database. Genetic Algorithms use interactive procedures that simulate evolutionary process. The evolutionary process is guided by selections based on individual's fitness. In each algorithm iteration (one generation) a new set of structures is created thought the exchange of information (bits and blocks) between structures previously selected from previous generation [27]. New structures are generated randomly with some probability and included in the population. The result tends to be an increasing on individual's fitness. This algorithm is structured in a way that a system's information can be codified like a biological chromosomes. Each value on the sequence usually represents a system variable.

As an example of application [28] uses a GA to evolve satisfactorily the power, direction and time to control motors of a robotic arm. The work on [29] presents a GA that evolve values of power and time to perform robotic walk. The work on [30] presents a GA to evolve the way a single mobile robot explores an unknown environment. These works show satisfactory results for static environments, [31] describes a possible solution to the problem of operating in dynamic environments where a robot navigates using GA, the robot has sensors for identification of obstacles and when a possible collision is detected the robot stops and reactivates planning mode using GA.

IV. Group formation

A. Simulator

In order to build a real physical implementation of this system, we must do the development and test before on realistic simulation environments. Robotic system's simulation is specially necessary in case of big, expensive or fragile robots because it's a extremely powerful tool to eliminating resources waste [5]. A large number of simulators has been evaluated, where the motivation to a new simulator development's choice can be seen in [1]. We use C++ as the programming language. A 2D version was developed with SDL [32] library and a 3D version was developed to support physically simulated robots on irregular land using OSG [33] (3D graphics), ODE [10] (physical realism) and Demeter [34] (irregular land). The simulator should be able to reproduce disaster environment for multi-robotic system's perform. We propose the situation of a forest fire, so, in this case a robot squad has the purpose of combat the forest fire acting by creating firebreaks around the fire. The Figure 3(a) represents the operation.

The implementation of the prototypes initiated with the creation of a map that combines information on vegetation, topography and behavior of fire. A detailed description of this simulator can be seen in [1], [8]. Study about forest models and residuals are very important for simulation models improvements [8]. The creation of maps was based on topographic charts and the forests fuel model of Ministry of Agriculture of Brazil. We uses a hidden matrix under land for vegetation simulation and correct fire propagation. This matrix has, for each land area, the present kind of vegetation. Considering wind orientation and the kind of vegetation is possible to build fire propagation's simulation. Fire propagation speed respects the model from [35].

B. GA description

The GA application for robotic group formation used GAlib library [36]. The algorithm optimizes fire combat position for each robot on group, specifically: (i) Initial combat position for each member of the group (beginning point of firebreak creation); (ii) Final combat position for each member of the group (final point of firebreak creation). These positions are send by command messages to activate the robots. To make the simulation is necessary: (i) Knowing the available number of robots; (ii) Knowing robot's operation speed; (iii) Robot's initial position; (iv) Having the ability to simulate fire propagation. To simulate fire

Table I
CHROMOSOME STRUCTURE (GROUP OF FOUR ROBOTS).

Gene	Function	Min. value	Max. value
0	Initial angle of robot 0	0,0º	360,0º
1	Final angle of robot 0; initial of robot 1	0,0º	360,0º
2	Final angle of robot 1; initial of robot 2	0,0º	360,0º
3	Final angle of robot 2; initial of robot 3	0,0º	360,0º
4	Final angle of robot 3	0,0º	360,0º
5	Initial radius of robot 0	10,0m	100,0m
6	Final radius of robot 0; initial of robot 1	10,0m	100,0m
7	Final radius of robot 1; initial of robot 2	10,0m	100,0m
8	Final radius of robot 2; initial of robot 3	10,0m	100,0m
9	Final radius of robot 3	10,0m	100,0m

propagation is necessary: (i) Getting the initial fire position; (ii) Getting wind direction; (iii) Getting a simplified copy of the map (land and vegetation). This set of proposed information can be totally obtained by sensors. Initially a chromosome was proposed where each robot position where independent, as no satisfactory results where found with some simulations, we proposed a new chromosome where a final robot position is the next robot's initial position, as presented in Table I.

The coordinates of operation are calculated applying Eq. 1 and 2 to the chromosome. Where (x_f, y_f) is the robot's final position, (x_a, y_a) is the starting position of the fire, r_i is the radius (gene 5 to 9) and a_i is the angle (gene 0 to 4). The radius and the angle are specifics to each operation of each robot (initial and final coordinate of firebreaks creation).

$$x_f = x_a + r_i \cdot \cos(a_i) \quad (1)$$

$$y_f = y_a + r_i \cdot \sin(a_i) \quad (2)$$

Related to GAs parameters, we use overlapping populations model (GASteadyStateGA) proposed by [37] and alleles (GARealAlleleSetArray) that limit value set generated for each attribute (radius between 10 and 100 and angles between 0 and 360 degrees). The use of alleles reduces the search space. Also, we used real genome (GARealGenome) optimized for float point numbers. Comparative analysis involving binary and float point representations showed that floating point representations has significantly advantages principally related to precision and convergence speed [38], [39]. Selection scheme used was Stochastic Remainder Sampling Selector (GASRSSelector) that has a better performance compared with roulette scheme [38]. Subsection IV-D describes evaluations with genetic parameter changes.

C. Fitness

The fitness function guides genetic algorithm's optimization. The proposed model has a fitness function that is related with saved vegetation area and combat units usage rate (firefighters robots). The developed fitness accumulates: (i) Total burned area: try to minimize burned area, (ii) Firebreak total area: try to minimize robot's work area, avoiding firebreak building on non-risk areas, (iii) Try to minimize difference between general average of useful firebreaks in relation to each individual useful firebreak, equalizing worked areas. The GA tries to minimize the fitness function value, that means less burned vegetation, less created firebreaks, and less difference between the size of firebreaks of each robot.

D. Experiments and results

Gaussian mutation (GARealGaussianMutator) and uniform mutation (GARealUniformMutator) where used. In the first case, when a reasonable chromosome is identified, small adjustments are realized (genes are changed by gaussian distribution). Second case changes a number for another random one, providing abrupt changes on values. All cases presented satisfactory results. The parameter that has bigger impact on fitness calculation is the Total Burned Area, so is an abrupt fitness fall on graphics when the simulation can already put out the fire. Simulations with 2 and 4 robots have been made. These simulations demonstrate that AG can obtain adequate solutions for the proposed problem. Many simulations have been made for the purpose of fitness evolution graphics observation.

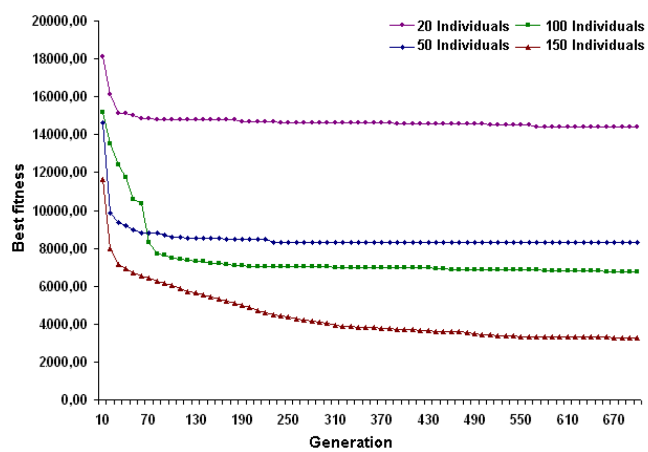


Figure 1. Evolution of fitness according to number of generations and individuals (group of four robots).

The evolution of fitness, to four firefighter's robots, can be seen in Figure 1, presenting the average of three simulations (gaussian mutation, 90% crossover rate, 10% mutation rate). Wind propagation simulation considered west-east wind (270º) and relative speeds 7km/h, robot navigation speed 35km/h and robot positioning on a base that is 2km far from fire's initial position. Figure 1 shows that the best fitness is obtained with a 150 individuals population. Between 400 and 700 generations, fitness is almost stabilized. Table II shows the best chromosomes resultant of three simulations using the described parameters. Genetic algorithm's best individual is selected to be applied the Eq. 1 and 2, so each robot performance's initial and final position is given.

Figure 2. (a) and (b) satisfactory results of the AG (150 individuals and 700 generations). (c), (d), (e) and (f) unsatisfactory results (less individuals).

This position is send by message to firefighters robots that navigate to initial coordinate and make a firebreak until the final coordinate.

The Figures 2(a) and 2(b) presents 2D visualization of satisfactory results. Using 20, 50, 100 and 700 population individuals the evolution generated unsatisfactory results; Figures 2(c), 2(d), 2(e) and 2(f) present these visualization (with unsatisfactory results). Figures 2(c) and 2(d) uses 20 population individuals and 700 generetion, in Figure 2(c) the fire is not stopped by the firebreak. Figure 2(e) uses 50 population individuals and 700 generetion, but the firebreak is is not well distributed among the robots. Figure 2(f) uses 100 population individuals and 700 generetion, but the firebreaks of the area is too large in relation to what would be necessary.

Table II
BEST CHROMOSOMES (RESULTANT OF THREE SIMULATION).

	Simulation		
Gene	A	B	C
0	225.72	224.89	134.82
1	199.26	200.77	142.65
2	174.12	177.86	172.33
3	155.20	160.68	196.14
4	136.38	136.64	244.84
5	27.35	28.05	54.94
6	30.45	29.75	42.95
7	33.94	30.58	35.84
8	38.08	31.12	30.37
9	35.96	33.24	26.33

The Figure 3 shows the satisfactory result applicated on 3D prototype. It can be seen that firefighter's robots surround perfectly the fire and create firebreaks on a satisfactory way. Fire propagation speed was arbitrarily reduced for this simulation because the ability of sending delay notices between robot's isn't developed, it occurs on irregular land navigation and it's necessary to deviate from obstacles which ends up navigation. Experiences with 2 robot groups has been realized either with chromosome adaptation (Table I shows the chromosome for four robots). Gaussian and uniform mutation achieved 100% satisfactory results. Maximum, medium and minimum fitness convergence appeared for all cases of 2 and 4 robots using as parameters 150 individuals and at least 400 generations. In all 20 simulations we have been performed with suggested parameters, 100% of the simulations could surround the fire in a satisfactory way. Some simulations using different navigation speed and fire propagation have been made and achieved good results but are not detailed on this paper. For navigation (Figure 4) robots use artificial neural networks detailed in [9]. More details can be found in [40].

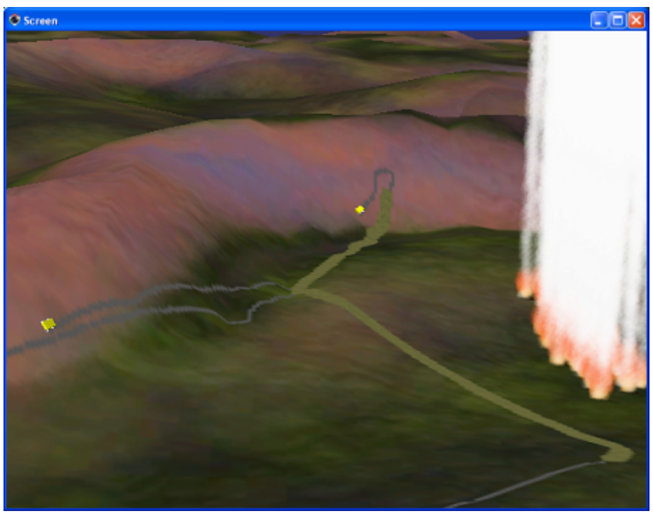
V. FUTURE WORK

Some approaches may be considered as future work: (i) a detailed study on fail-tolerance methods for the combat operation, (ii) the development of heuristics to make evolution faster; (iii) studies of other techniques of group formation, such the swarm based models [7], [23] and the Market-based Approaches [41], (iv) the sophistication of the fire simulation model. After the evaluation of these approaches, the system must be built using real robots.

VI. CONCLUSION

This paper detailed the model, the implementation and evaluation of the Genetic Algorithm's (GA) efficiency when applied to robotic group formation and coordination. The robotic task in this paper is performed over a natural disaster, simulated as a forest fire; the simulator is detailed in [1]. The robot squad mission is to surround the fire and avoid fire's

(a)



(b)

Figure 3. Satisfactory results of the GA (150 individuals and 700 generations). (a) Four mobile robots creating a firebreak. (b) Two mobile robots creating a firebreak.

propagation. Experiments have been made with different chromosome models and several parameter's variation. This paper describes all performed experiments detailing all sets of parameters, including positive and negative results. The simulation's results showed that with an adequate set of parameters is possible to get satisfactory strategic positions for a multi-robotic system's operation; furthermore, this GA solution can be applied on similar activities.

Acknowledgment

The authors acknowledge the support granted by CNPq and FAPESP to the INCT-SEC (National Institute of Science and Technology – Critical Embedded Systems – Brazil), processes 573963/2008-8 and 08/57870-9. Also acknowledge Capes for financial support.

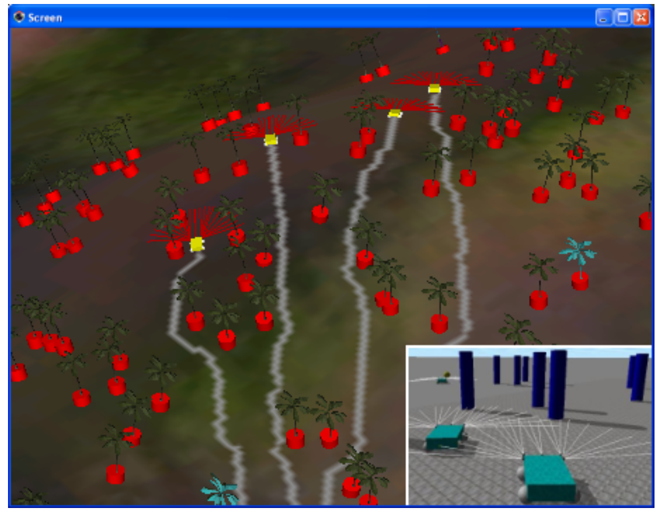


Figure 4. Detailed view of navigation with obstacles avoidance.

References

[1] G. Pessin, F. S. Osório, S. R. Musse, V. Nonnenmacher, and S. S. Ferreira, "Desenvolvimento de um ambiente para simulação de robótica móvel em Áreas florestais," in *Proceedings of VI Simpósio de Informática da Região Centro do RS (SIRC-RS'07)*. Santa Maria, RS, Brazil: Centro Universitário Franciscano (UNIFRA), 2007, pp. 1–8.

[2] G. Dudek and M. Jenkin, *Computational Principles of Mobile Robotics*. Cambridge, London, UK: The MIT Press, 2000.

[3] G. A. Bekey, *Autonomous Robots: From Biological Inspiration to Implementation and Control*. Cambridge, Massachusetts, USA: The MIT Press, 2005.

[4] S. Nolfi and D. Floreano, *Evolutionary Robotics: The Biology, Intelligence, and Technology of Self-Organizing Machines*. Cambridge, Massachusetts, USA: The MIT Press, 2000.

[5] J. Go, B. Browning, and M. Veloso, "Accurate and flexible simulation for dynamic, vision-centric robots," in *Third International Joint Conference on Autonomous Agents and Multiagent Systems (AAMAS'04)*, vol. 3, New York, 2004, pp. 1388–1389.

[6] P. Osagie, "Distributed control for networked autonomous vehicles," Master's thesis, KTH Computer Science and Communication, Royal Institute of Technology, Sweden, 2006.

[7] F. Mondada, L. M. Gambardella, D. Floreano, and M. Dorigo, "The cooperation of swarm-bots: Physical interactions in collective robotics," *IEEE Robotics and Automation Magazine*, vol. 12, pp. 21–28, 2005.

[8] G. Pessin, F. S. Osório, S. R. Musse, V. Nonnenmacher, and S. S. Ferreira, "Simulação virtual de agentes autônomos para a identificação e controle de incêndios em reservas naturais," in *Anais do IX Symposium on Virtual and Augmented Reality (SVR'07)*, Petrópolis, RJ, Brasil, 2007, pp. 236–245.

[9] G. Pessin, F. S. Osório, and S. R. Musse, “Simulação virtual da evolução de estratégias e do controle inteligente em sistemas multi-robóticos,” in *Anais do X Symposium on Virtual and Augmented Reality (SVR’08)*, João Pessoa, PB, Brazil, 2008.

[10] R. Smith, “Open dynamics engine website, www.ode.org,” 2007.

[11] IdMind, “Projecto raposa: Robot semi-autônomo para operações de salvamento raposa, http://raposa.idmind.pt,” 2007.

[12] A. R. M. Macedo, A. R. L. Macedo, and J. B. F. Duarte, “Robótica aplicada ao combate a incidentes,” *Revista TN Petróleo*, no. 53, pp. 108–113, 2007.

[13] Boeing, “The boeing company website, www.boeing.com/defense-space/military/x-45/index.html,” 2007.

[14] Dassault, “Dassault aviation website, www.dassault-aviation.com,” 2007.

[15] Trinity, “Firefighting robot contest, www.trincoll.edu/events/robot,” 2007.

[16] PennState, “Penn state mobile robotics program website, http://www.ecsel.psu.edu/ avanzato/robots/contests/firefighting/index.htm,” 2007.

[17] E. R. Costa, M. L. Gomes, and R. A. C. Bianchi, “Um mini robô móvel seguidor de pistas guiado por visão local,” in *VI Simpósio Brasileiro de Automação Inteligente (SBAI)*, 2003, pp. 710–715.

[18] Y. Zhao and E. G. Collins, “Robust automatic parallel parking in tight spaces via fuzzy logic,” *Robotics and Autonomous Systems*, vol. 51, pp. 111–127, 2005.

[19] M. R. Heinen, F. S. Osório, F. J. Heinen, and C. Kelber, “Seva3d: Using artificial neural networks to autonomous vehicle parking control,” in *Proceedings of IEEE World Congress On Computational Intelligence, International Joint Conference On Neural Networks (IJCNN’06)*. Vancouver, Canadá: IEEE Press, 2006, pp. 4704–4711.

[20] Darpa, “Darpa grand challenge webpage: Defense advanced research projects agency, www.darpa.mil/grandchallenge,” 2007.

[21] H. Yamaguchi, “Adaptive formation control for distributed autonomous mobile robotgroups,” in *IEEE International Conference on Robotics and Automation*, vol. 3, Albuquerque, NM, USA, pp. 2300–2305.

[22] T. Balch and R. C. Arkin, “Behavior-based formation control for multi-robot teams,” *IEEE Transactions on Robotics and Automation*, vol. 14, no. 6, pp. 926–939, 1998.

[23] M. Dorigo, V. Trianni, E. Sahin, R. Gro, T. Labella, G. Baldassarre, S. Nolfi, J. Deneubourg, F. Mondada, D. Floreano, and L. Gambardella, “Evolving self-organizing behaviors for a swarm-bot,” *Autonomous Robots*, vol. 17, pp. 223–245, 2004.

[24] J. Holland, *Adaptation in Natural and Artificial Systems*. Ann Arbor, Michigan, USA: The University of Michigan Press, 1975.

[25] M. Mitchell, *An Introduction to Genetic Algorithms*. The MIT Press, 1996.

[26] A. C. F. Carvalho, A. P. Braga, and T. B. Ludermir, *Sistemas Inteligentes: Fundamentos e Aplicações*. Manole, 2003, ch. Computação Evolutiva, pp. 225–248.

[27] D. E. Goldberg, *Genetic Algorithms in Search, Optimization and Machine Learning*. Boston, MA, USA: Addison-Wesley Professional, 1989.

[28] J. A. Gonzalez and M. Marengoni, “Controle baseado em algoritmo genético para um braço robótico móvel,” in *Proceedings of VII Simpósio Brasileiro de Automação Inteligente (SBAI’05)*, São Luís, MA, Brazil, 2005.

[29] M. R. Heinen, “Controle inteligente do caminhar de robôs móveis simulados,” Master’s thesis, Universidade do Vale do Rio dos Sinos (Unisinos), 2007.

[30] Y. Zhou, “An area exploration strategy evolved by genetic algorithm,” Master’s thesis, University of Georgia, 2005.

[31] H. Burchardt and R. Salomon, “Implementation of path planning using g.a. on mobile robots,” in *Proceedings of IEEE Congress on Evolutionary Computation (CEC’06)*, Vancouver, BC, Canada, 2006.

[32] Sdl, “Simple directmedia layer website, www.libsdl.org,” 2007.

[33] OSG, “Open scene graph, osg community website, http://www.openscenegraph.com,” 2007.

[34] Demeter, “Demeter terrain engine, www.tbgsoftware.com,” 2007.

[35] L. P. Koproski, “O fogo e seus efeitos sobre a heperto e a mastofauna terrestre no parque nacional de ilha grande,” Master’s thesis, UFPR, 2005.

[36] M. Wall, “Genetic algorithms library, massachusetts institute of technology, http://lancet.mit.edu/ga,” 2007.

[37] K. Dejong, “The analysis and behaviour of a class of genetic adaptive systems,” Ph.D. dissertation, University of Michigan, USA, 1975.

[38] Z. Michalewicz, *Genetic Algorithms + Data Structures = Evolution Programs*. New York, USA: Springer-Verlag, 1996.

[39] D. E. Goldberg, “Real-coded genetic algorithms, virtual alphabets, and blocking,” *Complex Systems*, vol. 5, pp. 139–167, 1991.

[40] G. Pessin, “Evolução de estratégias e controle inteligente em sistemas multi-robóticos robustos,” Master’s thesis, Universidade do Vale do Rio dos Sinos, Available at http://pessin.googlepages.com/disspessin2008.pdf, 2008.

[41] M. B. Dias, R. Zlot, N. Kalra, and A. Stentz, “Market-based multirobot coordination: A survey and analysis,” *Proceedings of the IEEE*, vol. 94, pp. 1257–1270, 2006.