DESIGN AND SIMULATION OF A COOPERATIVE ROBOTICS SYSTEM FOR EXPLORATION AND TRANSPORTATION TASKS

RICARDO ANDRES CASTILLO, GERMAN ANDRES VARGAS & OVER MUR LOZANO

DAVINCI Research Group, Department of Mechatronics Engineering, Universidad Militar Nueva Granada, Bogota, Colombia

ABSTRACT

Expansion of mobile robotics into new action fields introduces challenges for which multiple robot systems become an interesting option given the need for fault tolerance and maximizing performance (runtime, energy consumption) in highly complex tasks. This paper describes the current state of development of a collaborative multi-agent system (MAS) which integrates three distinct architectures built using the Robotis Bioloid educational robotics platform: a humanoid, a gripper-equipped vehicle, and a wheel-legged hybrid mobile robot. Simplified CAD models are imported into Webots simulation software, where separate controllers for each architecture are developed, as well as a supervisor controller which commands coordination of behaviors and tasks that each robot must execute. Preliminary results demonstrate lower path execution precision for the humanoid and vehicle compared to the hybrid. Thus, several distributed control strategies are evaluated and implemented for transportation tasks, which require high synchronization between all agents.

KEYWORDS: Multi-Agent System, Cooperative Robotics, Distributed Control, Webots

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INTRODUCTION

Massification of mobile robotics in the past 15 years allowed the scientific community to tackle complex new applications, where performance metrics such as runtime (Kelly, 2004), energy consumption (Bano, 2010) and fault tolerance are crucial for a robotic system to be considered a feasible and cost-effective solution (Castillo, 2013). When multiple robots are used in an application, mechanisms that incite cooperative work between them are required to maximize global efficiency (Vlassis, 2007). However, relations established between robots during coordination are not trivial (Merino, 2009), since temporal and kinematic constraints must be considered when breaking down a task into separate synchronous/asynchronous actions that each robot must perform (Zivanovic, 2006). A theoretical background for development of said mechanisms arose from the Multi-Agent System (MAS) paradigm, which studies computerized systems in which multiple rational agents interact (Vargas, 2015). The abstraction of a robot as an MAS agent is described as an autonomous computational process, capable of perceiving and acting upon its environment as well as communication with other agents to establish cooperation.

This article describes the development of a MAS based on three mobile architectures with varying manipulation and locomotion capabilities. Section 2 highlights preceding developments carried out at Universidad Militar Nueva Granada. Section 3 describes the hardware and individual capabilities of each robot architecture. Section 4 details simulation of individual architectures in a virtual environment, followed by simulation of a complete movement algorithm in section 5. Lastly, section 6 states and evaluates obtained test results.

PREVIOUS WORK AT UMNG

Within the scope of robotics research carried out at Universidad Militar Nueva Granada (UMNG), availability of multiple educational robotics platform for undergraduate mechatronics students led the DAVINCI Research Group to work in cooperative robotics. Given that low robot cost is a common key factor in this field, the RobotisBioloid platform was selected due to its versatility for assemble of diverse hardware configurations.

In the first approach in year 2012, the decision was made to assemble the MAS system using homogeneous agents (same hardware, physical architecture, and perception/actuation capabilities). Amongst 29 possible architectures predesigned by the manufacturer, the humanoid one was chosen due to its capacity for simultaneous manipulation and locomotion. Since the Bioloid platform is based on an 8-bit ATmega2561 microcontroller, computing power is not enough for on-board machine vision. Consequently, an additional agent was added to the system in charge of extracting the pose of any object of interest within the workspace (Kelly, 2004). When evaluating system performance in exploration, gathering and object transportation tasks, temporary instances in which agents could conform smaller work sub-groups were observed (Bano, 2010). Therefore, the second MAS iteration incorporated a DARwIn-OP humanoid robot into the system to coordinate these sub-groups at a local level. This humanoid shares the same kinematic model of the Bioloid robots. Subsequently, a logic-module based modelling enables use of a single motion controller and CAD model for all robots, as presented in Figure 1.

Figure 1: Unified Humanoid Agent Representation.

Though cooperation strategy results proved satisfactory, maximum system efficiency was limited by the robots' high error margin whilst executing planned paths, as well as their low movement speed in comparison to wheeled mobile robots. Taking these factors into consideration, the third and current iteration of the MAS involves heterogeneous robots: variations in hardware and physical architecture between robots provide specialized operation capabilities. These architectures are described in greater detail in the following section.

ROBOT ARCHITECTURES

Application of the MAS in exploration, gathering and object transportation tasks implicitly entails higher priority of manipulation and locomotion capabilities in the system's robots. To evaluate correlation between said capabilities and global system efficiency, three distinct physical architectures were established, one which balances both capabilities and the remaining two prioritizing one of the two capabilities in expense of lesser performance in the counterpart capability.

Humanoid

The humanoid architecture predesigned by the Bioloid manufacturer used in the first two iterations of the MAS did not have an end-effector or capable of object prehension.

Figure 2: Modified Humanoid Architecture.

Consequently, an individual robot agent was unable to collect an object by itself and was forced to cooperate with other agents synchronizing its movements. To provide greater autonomy to this architecture, two additional actuators are incorporated to its extremities as observed in Figure 2, now giving the humanoid a total of 20 controllable degrees of freedom. This added weight modifies the robot's dynamics, forcing use of lower movement speeds to maintain balance in the 16 possible gait patterns illustrated in Figure 3.

Figure 3: Gait Patterns for the Humanoid Architecture (Nakaura, 2002).

The humanoid platform possesses the highest manipulation capabilities in the system since it can vertically reposition itself according to the object of interest and pick it up through bimanual movements. In contrast, its locomotion capabilities are limited, due to its mass distribution hampering its movement speed, making it inefficient for traversing large extents of the workspace.

Gripper-Equipped Vehicle

This architecture consists of a mobile robot with four fixed-type wheels and a large gripper in the front, as shown in Figure 4. Since the wheels cannot be steered, the vehicle's kinematic behavior is equivalent to a differential mobile robot. Though its gripper size allows manipulation of larger objects when compared to the humanoid architecture, its kinematic constraints imply a higher amount of motions necessary to position the vehicle in a correct pose for object manipulation. Therefore, this architecture displays a balance between its manipulation and locomotion capabilities.

Figure 4: Vehicle Architecture with a Gripper Actuator.

Wheel-Leg Hybrid Mobile Robot

Higher robustness and fault tolerance of MAS systems has made them a prime candidate for Urban Search and Rescue (USAR) applications, where unstructured environments are commonplace. This has led to greater focus on hybrid mobile robots, which aim to combine inherent advantages of different types of locomotion (Vlassis, 2007): performance of legs in unstructured terrain, greater contact surface and traction of treads and speed and energy efficiency of wheels. As a first approach to this type of mobile robots, the Bioloid platform was used to assemble a wheel-leg hybrid, placing a fixed-type wheel at the end of each leg (the point that establishes contact with the ground), as displayed in Figure 5.

Figure 5: Vehicle Architecture with a Gripper Actuator.

In essence, the robot reserves legged locomotion for unstructured terrain, using wheeled locomotion as much as possible to reduce energy consumption. This platform does not possess an end-effector and consequently has no manipulation capabilities. On the contrary, the possibility of steering its wheels by moving the legs provides the highest locomotion capabilities of all three platforms.

Table 1: Architecture Efficiency According To Performed Task

	Humanoid	Vehicle	Hybrid
Exploration	Minimal	Medium	Maximal
Gathering	Maximal	Medium	-
Object transport	Medium	Medium	Medium

Table 1 summarizes individual capabilities of each architecture according to the task in which the MAS is applied. The following step is simulation of movement patterns to guarantee the robots' structural integrity, which is described in the following section.

SIMULATION IN WEBOTS

The geometrical complexity of the system's robots' physical architectures demands robust simulation software, with functionalities that streamline implementation of said architectures and their workspace in a 3D virtual environment (See figures 6, 7 and 8).

Based upon these requirements, Webots simulation software has been chosen since the MAS' first iteration due to its support for several programming languages, supervision interfaces for modification of simulation parameters during runtime and its use of the *Open Dynamics Engine* (ODE) to represent contact and collision physics.

Architecture Implementation

As a measure for streamlining development of a virtual environment, Webots enables importation of a robot's CAD models (in VRML 2.0 format). Through this procedure the robot's boundaries are represented by a polygonal mesh stored as an array of XYZ coordinates. Following this step physical properties such as mass, density and materials must be configured, as well as assembly relationships where translation/rotation joints or actuators are present.

Figure 6: Humanoid Simulation Model.

Figure 7: Gripper-Equipped Vehicle Simulation Model.

Figure 8: Wheel-Leg Hybrid Simulation Model.

Given that Webots already includes a model of the DARwIn-OP humanoid, said model can be used to represent the MAS' Bioloid humanoid. Therefore, it is only necessary to import the two remaining architectures. Simplified CAD models detailed from Figures 6 to 8 were created to reduce computational workload for the ODE engine.

Movement Evaluation

A necessary step to ensure proper autonomous operation of the MAS' architectures is local (embedded in each robot) implementation of actuation and perception capabilities. In terms of robot movement, this can be achieved by means of Central Pattern Generators (CPG) which store basic movement primitives for each architecture (Merino, 2009).

Taking into consideration that locomotion versatility is only put to the test when the robots approach an object of interest during gathering tasks, the majority of robot movement during system operation corresponds to workspace traversal by execution of planned paths. Widely studied techniques such as heuristic-based path planners (Zivanovic, 2006) are sufficient for the current scope of the project, requiring only frontal movements and in-place rotations. Therefore, a preliminary simulation in which a user can command each architecture's movement by keyboard commands was developed. It is important to note that said simulation was constrained to a static work environment and structured terrain.

MOVEMENT ALGORITHM

Once correct execution of movement primitives in each individual robot architecture was verified, the following step is formulation of a generalized movement algorithm. In said algorithm, a preliminary step is an analysis of the robots'

workspace, which must be done periodically as the workspace is dynamic over the course of system operation. Since an A* heuristic path planner was chosen, such analysis consists of discretizing the workspace by overlaying a grid and encoding key system information, such as coordinates of obstacles, robots, and objects of interest.

Afterwards, the planner generates paths leading the robots to the objects of interest, in which the heuristic will be determined by the corresponding capabilities of each architecture, as described in the previous sections. Path execution is carried out by an alternating sequence of forward motion and rotation primitives, monitored through the use of a counter and regulated by a system controller in charge of minimizing the position or orientation error according to the corresponding path segment primitive.

Figure 9: An Example of a Valid Random Object Distribution Before Simulation.

TESTS AND RESULTS

Performance of the movement algorithm was assessed throughout 15 tests (5 per architecture) in which the virtual environment contained the robot, an object of interest and up to four obstacles. All elements were located randomly at simulation start and the user verified the distribution to ensure no straight-line path between the robot and the object was possible. This is illustrated in Figure 9.

Table 2 presents all test results, where T denotes total execution time (in MM:SS format) and E denotes the total amount of motion corrections that the robot had to perform to compensate position or orientation error, according to the corresponding path segment.

Table 2: Architecture Performance Results for the Movement Algorithm

	Humanoid		Vehicle		Hybrid	
	<i>T</i>	<i>E</i>	<i>T</i>	<i>E</i>	<i>T</i>	<i>E</i>
1	2:09	5	1:43	2	1:30	1
2	2:15	8	1:47	3	1:28	0
3	2:11	7	1:40	1	1:34	2
4	2:02	4	1:55	4	1:32	1
5	2:06	5	1:51	4	1:39	3

CONCLUSIONS

Systems tests demonstrated existence of a proportionality relationship not only between locomotion capabilities and total runtime, but between said capabilities and the total amount of path execution errors requiring compensation as well. This is due to the repetitive heading changes that the paths require given the previous discretization of the continuous environment by means of a grid. Incorporation of an intermediate path segment smoothing step to minimize the amount and magnitude of said heading changes must be evaluated.

When comparing system architectures, the increased number of path execution errors displayed by the gripper-equipped vehicle can be associated to its higher ground friction during rotation motions, since unlike the hybrid this architecture cannot steer its wheels. In the humanoid architecture's case, the manufacturer-predefined gait patterns are prone to notorious oscillation of the humanoid's torso, thus generating incremental error buildup in each path segment. Said oscillations can only be mitigated by incorporating a Zero Moment Point (ZMP) based controller in the architecture (Vargas, 2015).

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Ricardo A. Castillo was born in Colombia. He received his B.Eng. in Mechatronics Engineering in Universidad Militar Nueva Granada in 2004, and his M.Sc. and Ph.D. in Mechanical Engineering in the University of Campinas – UNICAMP, Brazil in 2010 and 2015 respectively, for his work on coordination and indirect communication strategies for mechatronic systems. Since 2005 he is a full-time Professor and Researcher in the Department of Mechatronics Engineering at Universidad Militar Nueva Granada. His current research projects deal with collaborative modular robotics and mobile autonomous robotics.

Germán A. Vargas was born on July 6th in Bogotá, Colombia. He received his B.Eng. and M.Sc. in Mechatronics Engineering in Universidad Militar Nueva Granada in 2012 and 2018 respectively. Currently, he is an adjunct professor for robotics at Escuela Tecnológica Instituto Técnico Central. His current research topics include simulation of path planning algorithms for mobile robots.

Over Mur Lozano was born in Colombia. He received his B.Eng. in Mechatronics Engineering in Universidad Militar Nueva Granada in 2017. His current research topics include modular robotics, homogeneous and heterogeneous multi-agent systems and mobile robotics.