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Multi-Modal Locomotion Robotic Platform Using Leg-Track-Wheel Articulations*

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Abstract. Other than from its sensing and processing capabilities, a mobile robotic platform can be limited in its use by its ability to move in the environment. Legs, tracks and wheels are all efficient means of ground locomotion that are most suitable in different situations. Legs allow to climb over obstacles and change the height of the robot, modifying its viewpoint of the world. Tracks are efficient on uneven terrains or on soft surfaces (snow, mud, etc.), while wheels are optimal on flat surfaces. Our objective is to work on a new concept capable of combining different locomotion mechanisms to increase the locomotion capabilities of the robotic platform. The design we came up with, called AZIMUT, is symmetrical and is made of four independent leg-track-wheel articulations. It can move with its articulations up, down or straight, allowing the robot to deal with three-dimensional environments. AZIMUT is also capable of moving sideways without changing its orientation, making it omnidirectional. By putting sensors on these articulations, the robot can also actively perceive its environment by changing the orientation of its articulations. Designing a robot with such capabilities requires addressing difficult design compromises, with measurable impacts seen only after integrating all of the components together. Modularity at the structural, hardware and embedded software levels, all considered concurrently in an iterative design process, reveals to be key in the design of sophisticated mobile robotic platforms.

Keywords: multi-modal locomotion, omnidirectional, stair-climbing, mobile robotic

1. Introduction

The most common way to build a mobile robot is to use two-wheel drive with differential steering and a rear balancing caster. Controlling the two motors independently makes the robot holonomic in its motion. Such robots can work well indoors on flat surfaces and in environments adapted for wheelchairs. Many commercial platforms based on this locomotion mechanism exist. Using such platforms allows to focus on two important aspects regarding intelligent autonomous robots: perception and decision-making. However in real-life settings it is necessary to deal with uneven terrains (outdoors and also indoors): stairs and obstacles that robots would need to go over or to pass across limit the use of conventional wheeled robots. Also, compared to moving on flat surfaces, the design of a robotic platform having to work in such conditions has to deal with more severe constraints such as weight, power and size. Designing robots that can address the complexity

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of operating in three-dimensional worlds moves the focus to the locomotion capabilities of autonomous machines, which are as important as perception and decision-making. In fact, the locomotion aspect of a robot plays a direct role in the perceptual and reasoning capabilities it requires to operate in these complex conditions.

One motivation in starting out this project was to design a robot capable of handling staircases, straight or circular, in home environments. Humanoid robots are surely one design solution to deal with such three-dimensional settings. Like humans, a robot with two legs would be able to go up and down stairs. Since stairs are structures built by humans, making humanoid robots allows it to be compatible with human-structured environments. Nevertheless, this may not be the most appropriate solution. For instance, a legged robot requires active control algorithms for the dynamics of the robot, e.g., to keep its balance (which usually requires higher energetic needs). Also, a robot with legs cannot generally move as fast as a robot with wheels, or work well on soft surfaces (snow, mud, etc.). Exploiting many locomotion modalities might be more appropriate, like combining legs to wheels and tracks. It would allow a robot to use the most appropriate locomotion mechanism for the prevailing conditions in the environment. This is kind of a natural solution since humans use various types of machines (which can be seen as modules) like cars, bicycles, snowmobiles, etc., to assist them in traveling more efficiently and compensate for the limitations of their abilities to move in the world. But unlike humans, it is possible for robots to combine the advantages of all by integrating multiple locomotion mechanisms to its structure.

This paper describes the design of a new robotic platform that we named AZIMUT. AZIMUT is made of four independent leg-track-wheel articulations and can generate a wide variety of movements. This concept allows the robot to be capable of holonomic and omnidirectional motion, climb or move over obstacles, go up and down stairs (straight or circular). The design of AZIMUT involves expertise in mechanical engineering, electrical engineering, computer engineering and industrial design. Modularity in all of these design areas is a key specification for such large-scale project, in order to benefit from the knowledge gained over the different prototypes made and to be made of the robot, as for future technological advances for continuous improvements. It also allows the reconfiguration of the various types of locomotion mechanisms and capabilities (structural, electrical and processing) of the platform.

This paper is organized as follows. First, Section 2 reviews multi-modal robotic platforms. Section 3 gives a description of AZIMUT and its characteristics, outlining its locomotion capabilities. Section 4 presents its mechanical, hardware and software components. Section 5 describes the capabilities of the first prototype built. Section 6 summarizes the design challenges faced with AZIMUT, outlining the interdependencies between the disciplines and the difficult compromises that have to be made during the iterative design process of sophisticated mobile robotic platforms. Section 7 compares AZIMUT with similar robotic platforms, followed by conclusions and future work on the concept.

2. Multi-Modal Robotic Platforms

For this brief overview of multi-modal robotic platforms, we only address robots assembled as one integral structure, in opposition to reconfigurable robots made of an assemblage of homogeneous building blocks (e.g., Shen et al., 2002). Also, we focus on robots that combine wheels, legs or tracks for what can be called hybrid locomotion. Four main categories exist:

- Articulated-wheeled robots. These robots have wheels mounted on legs to move, either by using its wheels, by stepping, or by using both. Work-Partner (Ylonen and Halme, 2002; Halme et al., 1999), made from the Hybtor robotic platform, can use a locomotion mode that allows the robot to walk by keeping the wheels on the ground. GOAT,[1] Nanorover (Baumgartner et al., 1988), Walk'n Roll (Adachi et al., 1999), Hylos (Grand et al., 2002) and Roller-Walker (Hirose and Takeuchi, 1995; Hirose, 2000; Endo and Hirose, 2000) are all leg-wheels robots. GOAT has actuated wheels attached in a vertical plan placed at the center of the body of the robot, allowing the robot to flip. The Nanorover has both legs from one side connected at the center of its body. Walk'n Roll has small passive wheels attached to the front legs, and large active wheels on the rear legs. Hylos has four legs, each combining a two degrees of freedom (DOF) suspension mechanism with a steering and driven wheel. Roller-Walker has a special foot mechanism that changes between feet soles for the walking mode to passive wheels for the skating mode. Rocky 7 (Volpe et al., 1997) (an improved version of Sojourner Mars rover) and Shrimp (Estier et al., 2000) robots use six wheels on an articulated body. The Shrimp is able to passively overcome obstacles of up to two times its wheel diameter and can climb stairs with steps of over 20 cm (as long as the robot is correctly aligned with the stair). Octopus (Lauria et al., 2002) is the 'active' counterpart of the Shrimp with eight motorized wheels, four on each side, and a total of 15 DOF. Using information provided by its tactile wheels, the geometric angles of the articulations and the direction of the gravity field, the robot has to figure out how to control its motors to move over an obstacle. There is also the work of Steeves et al. (2002) who studied in simulation the dynamic behavior of a robotic platform with legs (sprung prismatic legs) equipped with wheels. A biped-type leg-wheeled robot is studied by Matsumoto et al. (1998) King, et al. (1991) propose a robot equipped with two front wheels and two sets of two-wheels attachment that can flip to climb over obstacles, placed at the rear end of the robot.

- Wheels and legs separated. On such robots the wheels and the legs are separated but act together to make the system move. Wheeleg (Guccione and Muscato, 2003), RoboTrac (Six and Kecskemethy, 1999) and ALDURO (Muller and Hiller, 1999) use two front legs and two back wheels. Chariot II (Dai et al., 1996) adds two back legs to this configuration, while Krovi and Kumar (1999) add two front legs to a conventional wheelchair.
- Articulated tracks. The Urban robot made by iRobot Inc. is one well-known example (Matthies et al., 2000) for this category. This robot has two side-tracks on each side, with two articulated tracks in the front that can do continuous 360 degree rotations and enable crossing curbs, climbing stairs and scrambling over rubble. For stairs, the robot deploys its side tracks, keeping good contact with the ground (making it more stable without requiring as much energy as to a humanoid robot). Soryu (Hirose, 2000) is a three-tracked snake-like robot that can actively bend both tracks attached to the ends of the robot.
- Wheels and tracks separated. Chen and Hsieh (2000) designed a robot equipped with four wheels and four tracks, two of each on each side, and that can be used in combination to create different motion patterns.

If we consider the designs described in the previous paragraphs, using articulated tracks offers the advantage of not requiring complex control mechanisms for preserving the stability and minimizing the vibration of the robot as it climbs stairs or moves over obstacles. The robot is able to keep a good contact with the ground, helping it to keep its stability. However, with the tracks deployed on the ground, friction increases and makes it harder for the robot to turn, especially if differential steering is used. In the following sections we describe how AZIMUT is capable of taking such constraints into consideration and combine the hybrid locomotion modes described above.

3. Design Characteristics of AZIMUT

To deal with three-dimensional environment, a robot like AZIMUT has to perform a wide variety of movements in three-dimensional space like moving forward and backward, turning, rotating on itself, lifting itself up, moving over obstacles, going up and down stairs, and moving in all directions (omnidirectional).

The design we came up with is shown in Fig. 1. AZIMUT is symmetrical and has four independent articulated parts attached to the corners of a square frame. Each articulated part combines a leg, a track and a wheel, and has three degrees of freedom. Overall, the robot uses 12 motors for its locomotion. The leg can rotate 360 degrees around the y axis and 180 degrees around the z axis. Once an articulation is placed at the right position, the system is designed to keep it in position without consuming electrical energy. This is illustrated by Fig. 2.

When the articulations are stretched, the robot can move by making the tracks rotate around the legs. As the articulations move upward toward the orientation

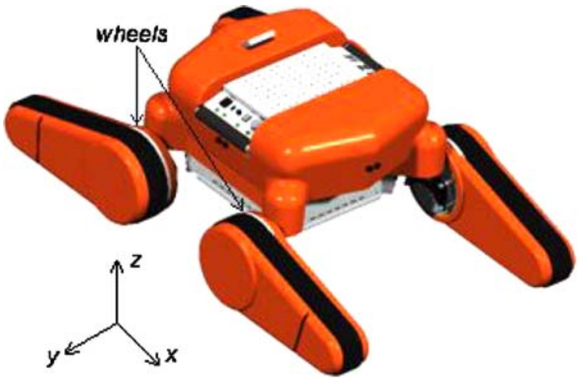


Figure 1. AZIMUT.

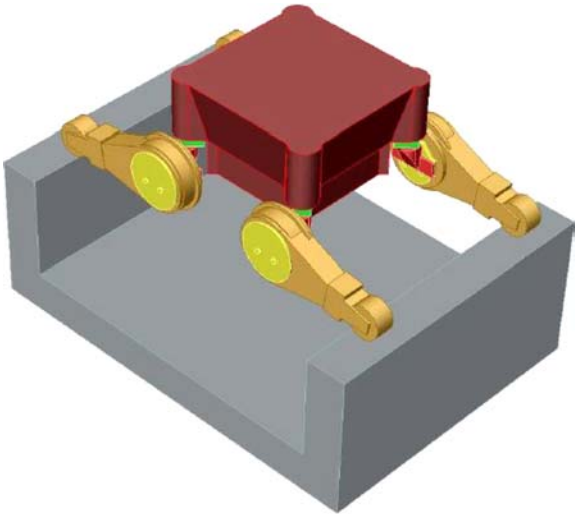


Figure 2. AZIMUT's articulations are designed to maintain the body in place without consuming electrical energy.

of the z axis, the point of contact of the leg with the ground moves from the track to the rubber strip fixed outbound of the attachment axle of the articulation, as shown in Fig. 3 (also visible in Fig. 8). This rubber strip creates a very narrow wheel that allows the robot to change the direction of an articulation with minimum friction.

The robot also offers nice features such as:

- two retractable side-handles to lift the robot;
- an accessory-fixing plate on the top of the chassis;
- a PDA interface for debugging the onboard embedded systems of the robot;
- two control panels allowing easy interface with the onboard systems of the robot;
- a sliding compartment for the onboard PC/104 computer, making computer upgrade and maintenance easier;
- bodywork attached to the chassis using easily accessible fixtures.

The dimensions of the robot are shown in Fig. 4. The dimensions were set in order to allow the robot to go through doors and to have a low center of gravity for good stability in negociating stairs.

By placing the articulations in different positions, AZIMUT can adopt various locomotion modes like the ones shown in Fig. 5. AZIMUT can move with its articulations parallel to the ground (a, g), on its wheels with the articulations up (b, c, d, e, f) or on the tracks with its articulations down (h). Differential steering can be used to make the robot turn in all of these modes, or the articulations can be placed in the desired direction of the robot. For instance, going from (b) to (f), the direction of the robot changes but not its orientation. The robot can turn on itself with minimum friction using mode (d). In (f), the robot can move using front or back two-wheel steering modes. The tracks are used in (g) and (h) to make the robot work on stairs, climb over obstacles or change its perceptual perspective of the world by raising itself up. Since each articulation is independent, the robot can create much more sophisticated modes. For instance, in can turn while climbing a staircase by changing the direction of the front and the back articulations. The robot can move with its front articulations stretched at 45 degrees in relation to the horizontal axis, which will allow the robot to climb over obstacles. The robot can cross its articulations and lift itself up when it gets stuck over an obstacle. Being omnidirectional, it would also be possible for a group of AZIMUT robots to change direction in a coordinated

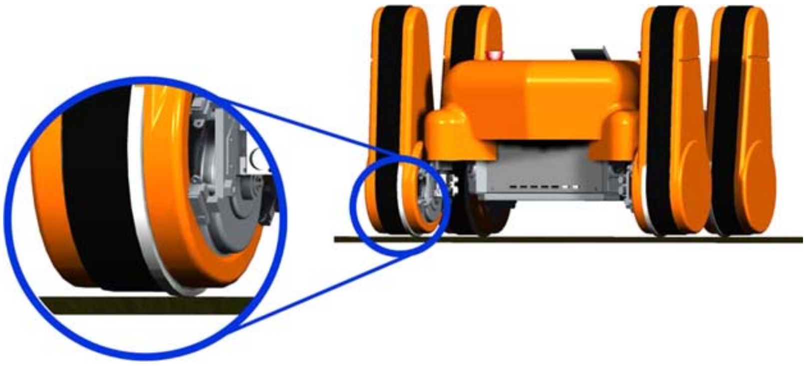


Figure 3. AZIMUT's wheel made of a rubber strip.

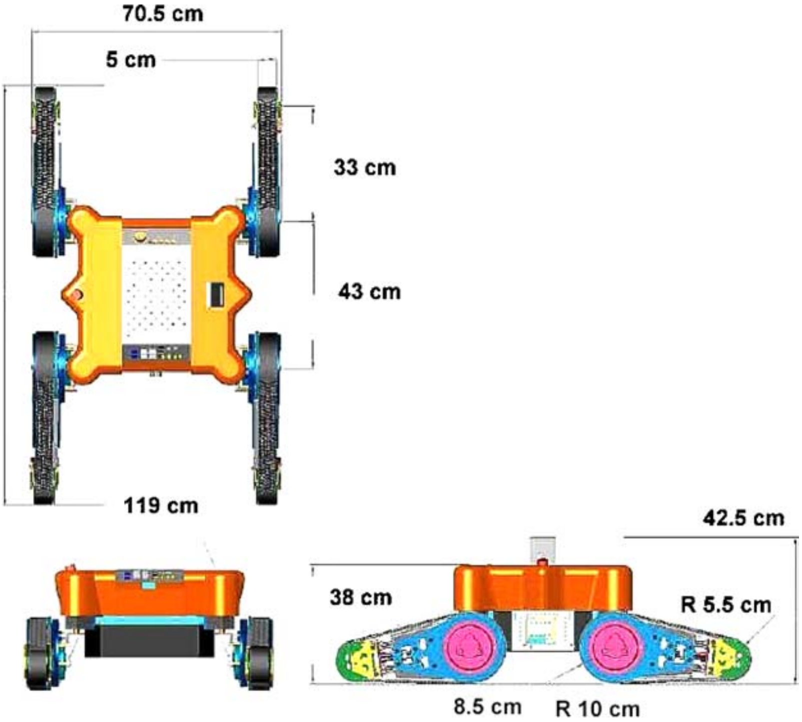


Figure 4. Top, front and side views of AZIMUT with its articulations stretched.

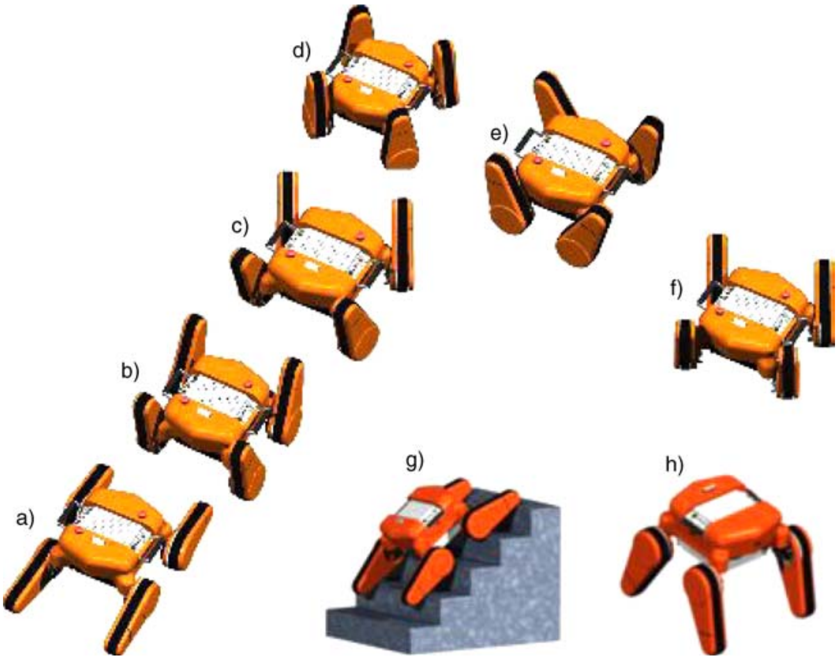


Figure 5. Locomotion modes of AZIMUT.

fashion while transporting together a common payload or large objects, without requiring a rotative fixture for the object to carry. Many other configurations can be imagined, and the 12 degrees of freedom on AZIMUT give the robot great flexibility and versatility in its locomotion capabilities.

4. AZIMUT's Design

Going from AZIMUT's concept to an actual prototype is a challenging endeavor. It requires the integration of sophisticated mechanical, electrical and computer components. Modularity at the structural, hardware and embedded software levels, all considered concurrently during the design process, reveals to be key in the design of such sophisticated mobile robotic platform.

4.1. Mechanical

The mechanical components of AZIMUT are grouped into six subsystems, as shown in Figs. 6 and 7. The four articulations are attached to the *Chassis* (a), which also holds the robot's hardware and its batteries. Two battery packs are placed at the bottom of the chassis, on the left and right side of the robot (see also Fig. 9), to keep the center of gravity of the robot as close as possible to the ground. The sliding compartment for the PC-104 form factor onboard computer is placed between the battery packs. The retractable side-handles and the accessory-fixing plate are attached to the chassis. The *Bodywork* (b) is there to protect the internal components and for aesthetic reasons. The other subsystems are for each articulation. The *Direction* subsystem (d) allows to change the direction of an articulation and to lock it in position. The *Propulsion* subsystem (e) makes the combination of the track-wheel rotate, and allows the rotation of an articulation around the *y* axis. Once placed in position, the articulation is locked mechanically. An articulation is made of an assemblage of a track with two wheels (the *Track-Wheel* subsystem (f)) and the *Tensor* (c)) to extend the tracks and support the weight of the robot when it moves with its articulations down.

Concerning the tracks, one particularity is that it is made of diamond profile conveyor belt (rubber) to

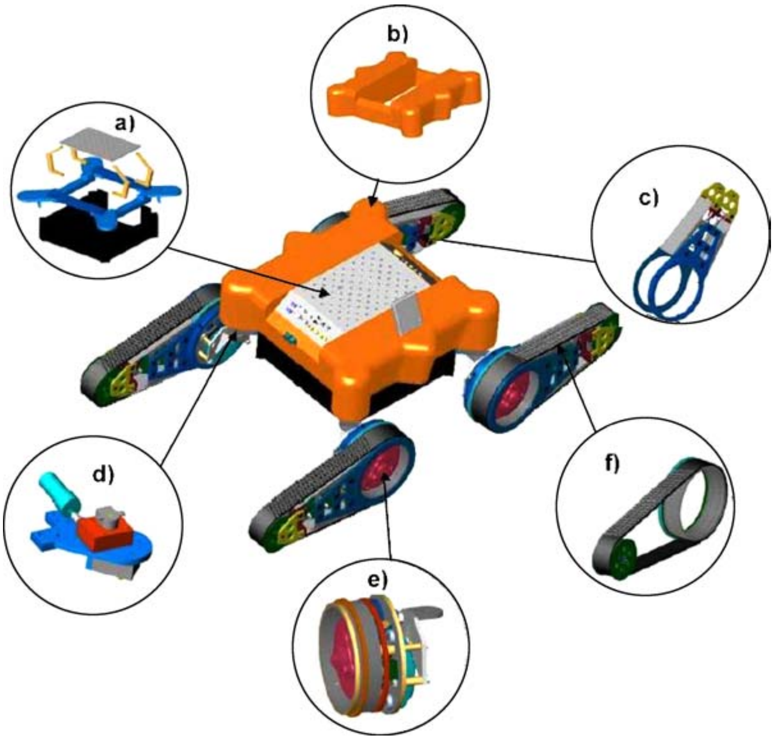


Figure 6. Position of AZIMUT's mechanical subsystems.

Figure 7. AZIMUT's mechanical subsystems.

Figure 8. Diamond-shape track left to the rubber strip for the wheel.

ensure maximum adherence with stairs without damaging them. Figure 8 shows a closeup picture of a track-wheel. The rubber strip for the wheel is on the right side of the track.

4.2. Hardware

AZIMUT's hardware is placed inside the body of the robot as shown in Fig. 9. From top to bottom, we can see the PDA, the circuit boards, sensors, the PC104 and the battery packs.

The usual approach for designing a mobile robot is to have a central microcontroller board to interface all of the sensors and actuators of the platform. This board has to be designed with all of the possible extensions (in terms of I/O and in the processing capabilities of the microcontroller) in mind. In opposition, AZIMUT's design at the hardware level is modular and is made of different subsystems that communicate with each other to exchange information and to coordinate their actions. Each subsystem has its own microcontroller, selected according to the processing requirements for the given subsystem. For AZIMUT, this approach is the most appropriate one because it allows to easily add devices to the robot, and to increase its robustness

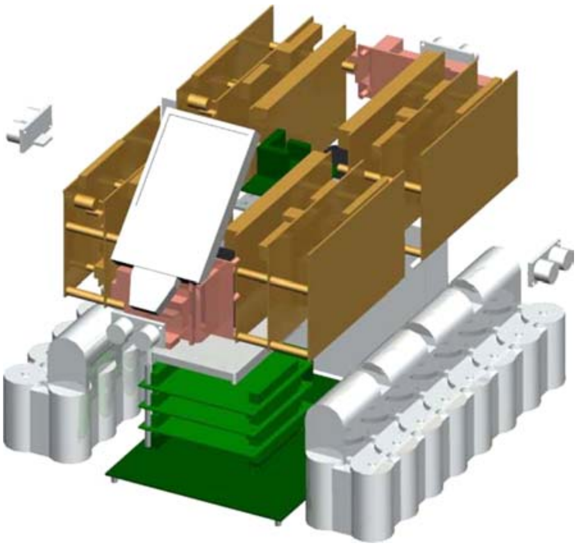


Figure 9. Position of the hardware elements inside the robot.

by distributing control over all its components or by adding redundancy if required.

Figure 10 represents the subsystems. Each articulation has its own *Local Control* subsystem (controlling its three motors in position, velocity and acceleration using PID controllers) and *Local Perception* subsystem. Limit switches are placed for each *Direction* subsystem to avoid having the articulation collides with the chassis. Each *Local Control* subsystem, directly in hardware, prevents giving power to *Direction* motors in the wrong direction when these limit switches are activated. The *Power* subsystem distributes energy coming from batteries or an external power source to all of the other subsystems. At any time, the power subsystem can switch on and off the batteries. Plugging the external power source also automatically switches the batteries off. The *User Interface* subsystem is there to interface the PDA with the other subsystems of the robot. The battery packs of the robot also provide power to the PDA, allowing to save its own batteries. The *Inclinometer* subsystem measures the inclination of the body of the robot. The *Remote Control* subsystem allows to send commands to the robot using a wireless remote control. The *General Control* subsystem manages positioning of the articulations when modes are changed to avoid interference, and monitors the states of the subsystems to insure safety of the platform. The *Computing* subsystem consists of the onboard computer used for high-level decision making (e.g., vision processing for a camera that would be used by the robot). All of the subsystems exchange information using the *Coordination* bus. The *Synchronization* bus is dedicated to synchronizing the control of the articulations (e.g., to make the articulations work together: such coordinated actions are subject to hard real-time constraints, and providing a specific data bus for this function avoid non-constant exchanges from other susbsystems sharing the bus).

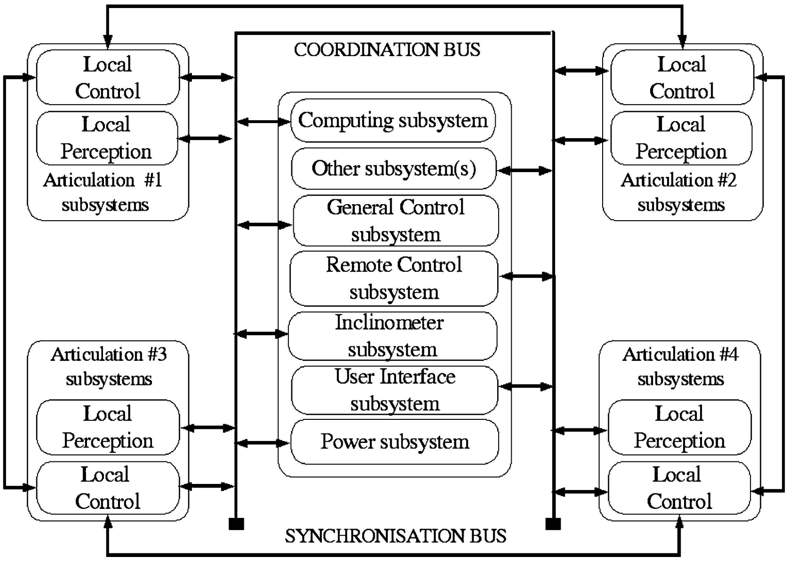


Figure 10. AZIMUT'S hardware subsystems.

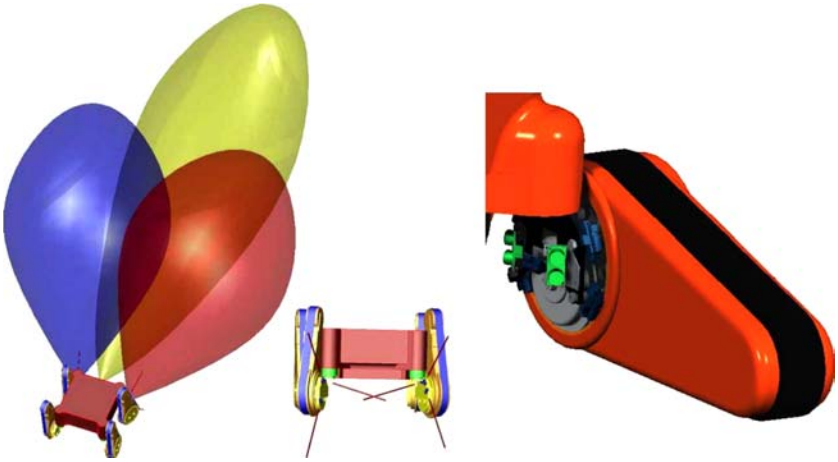


Figure 11. AZIMUT's onboard sensors: long and short range sonars (left), infrared (center) and an articulation (right).

The *Local Perception* subsystem of each articulation is made of one long-range ultrasonic sensor, two short-range ultrasonic sensors and five infrared range sensors, to detect objects and surfaces around the articulation. Figure 11 shows the perceptual zones using these sensors. Note that the sensors placed on the articulation can be used to scan an area by deplacing the articulation itself.

4.3. *Software*

There are two levels of software for AZIMUT: software for the subsystems, and software designed for the overall control of the robot.

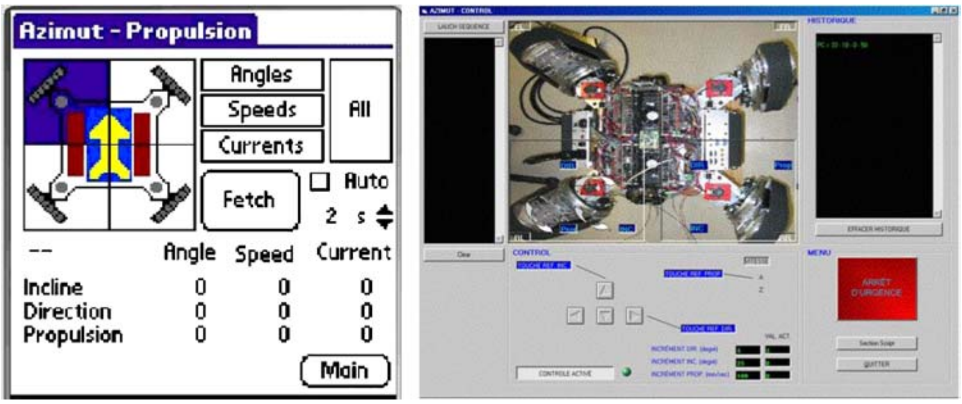
At the subsystem level, each subsystem follows a general procedure that allows it to examine conditions and requests posted on the bus, to complete a self-diagnostic test, to process a command or a request addressed to it, to get the data from its sensors, to process them, to give commands to its actuators and to transmit back its status on the bus. Each subsystem is designed to be implicitly safe: when not activated, a subsystem is in a state that will not put the robot in a dangerous condition. The *General Control* subsystem has the responsibility of activating the appropriate subsystems.

For the overall control of the robot, two types of software are used. The first is for testing and monitoring the states of the robot, using two different devices. One is implemented on a PDA. The PDA is a nice device for such purposes since it allows to use graphical representations of the status of the robot. A second interface is implemented on a remote computer connected to the *General Control* subsystem via a RS-232 serial link. This interface allows independent control of the motors and to monitor the states of motor encoders, the control loops and the data exchanged on the bus. Figure 12 shows the PDA and the remote computer interfaces. The picture is a top view of the robot's articulation (without the body) and is divided in four parts. Each part corresponds to one articulation, and the user just has to select the desired articulation to change and to monitor its states. Scripts of high-level commands can also be made for simultaneous control of the articulations.

The second type of software developed for the overall control of the robot is a simulator. Programmed in OPEN-GL, the simulator makes it possible to imagine control scenarios without having to use the actual prototype. Such scenarios can be the transitions made by the articulations to move from one locomotion mode to another, the position of the articulations as the robot goes up or down stairs, the possible interference between the articulations, etc. The simulator allows to develop the algorithms for the *General Control* and the *Computing* subsystems. Figure 13 illustrates the simulated environment.

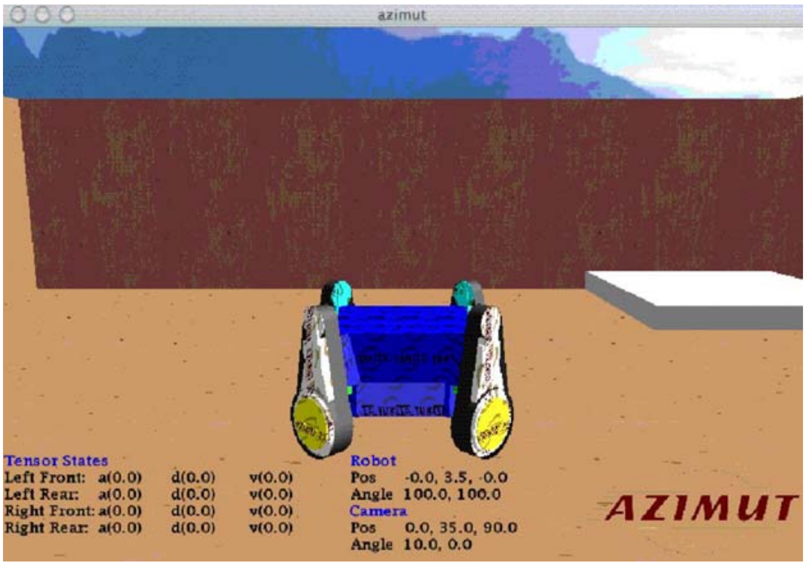
5. First Prototype

Figures 14 and 15 shows pictures of the first prototype of AZIMUT, completed in December 2002. The robot is made of more than 2500 parts. The motors used for propulsion are Ferrite ServoDisc motors. The direction and the rotation of the articulations use standard brush



--	Angle	Speed	Current
Incline	0	0	0
Direction	0	0	0
Propulsion	0	0	0

Figure 12. PDA interface (left) and the remote computer interface (right).



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Tensor States
Left Front:  a(0.0)   d(0.0)   v(0.0)
Left Rear:   a(0.0)   d(0.0)   v(0.0)
Right Front: a(0.0)   d(0.0)   v(0.0)
Right Rear:  a(0.0)   d(0.0)   v(0.0)

Robot
Pos    -0.0, 3.5, -0.0
Angle  100.0, 100.0
Camera
Pos    0.0, 35.0, 90.0
Angle  10.0, 0.0
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Figure 13. AZIMUT simulator.

motors. The directional speed (around the z axis) of the articulation is 120°/sec and the rotational speed (around the y axis) of the articulation is 45°/sec. The robot is equipped with two packs of 24 V Ni-MH cells.

Concerning the embedded systems used for the on-board distributed subsystems, this prototype uses four nanoMODUL164 from Phytec, equipped with Infineon C164CI 20 MHz microcontrollers (programmed in C using KEIL C166 compiler). These microcontrollers provide sufficient processing power to implement PID controllers for all of the three motors of an articulation. For subsystems other than the *General Control* subsystem, less processing capabilities are required. We designed a board that we named the PICoMODUL, shown in Fig. 16. It is made of a PIC 16F877, running at 20 MHz and programmed in C using PIC-C.

Both the nanoMODUL and the PICoMODUL are designed to be stacked on other boards made for specific functions, like a 100 Amp motor drive for an articulation, a sensor board for the *Local Perception* subsystem, a board that monitors the energy consumption and recharges of the batteries, a board for the RF remote control, etc. CAN 2.0B 1 Mbps buses are used for communication between the subsystems. Each subsystem has its own address on the CAN bus and can, using hardware and software filters, select only the messages addressed to it. A RS-232 to CAN bus bridge have been developed with a PIC microcontroller especially for the

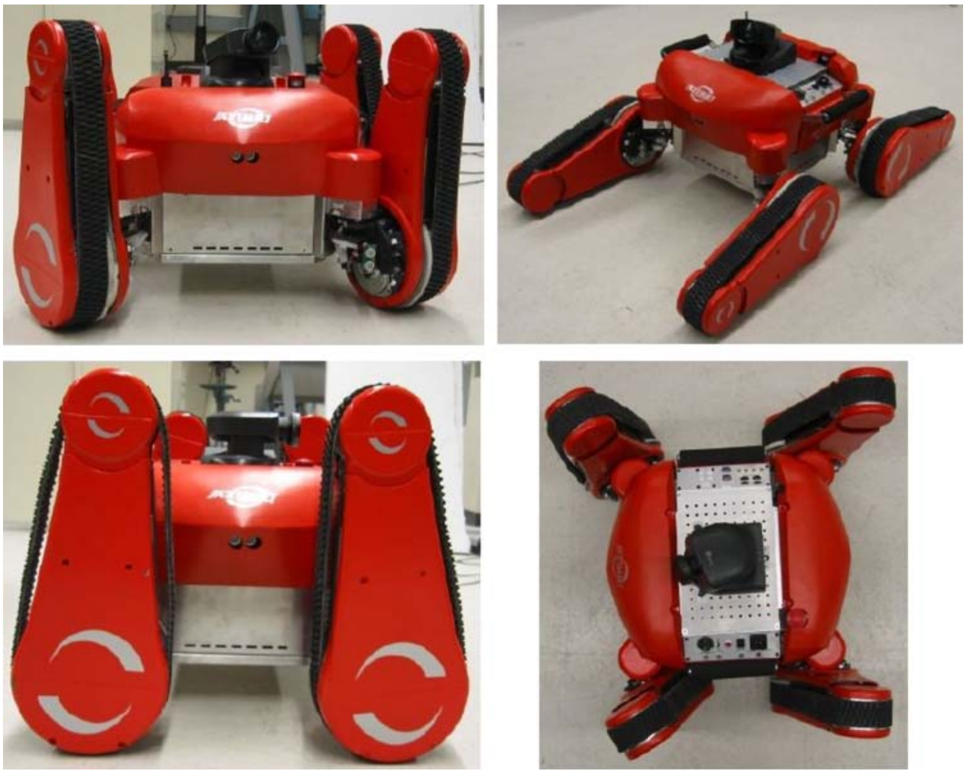

Figure 14. AZIMUT front view (top left), articulations stretched (top right), side view (bottom left), top view (bottom right).

PDA to be able to communicate on the CAN bus. A virtual CAN interface provided with the simulator enables the programmer to validate the application layer of the CAN protocol. Each message to the subsystems can be traced, validated and debugged in real-time.

The first prototype of AZIMUT demonstrates the capabilities of the robot in changing the orientation of its articulations for omnidirectional movements. Tests were done with a payload of 10.4 kg for all the positions of the articulations. The robot is also capable of moving with its articulations down, going through doors, or holding its weight as shown in Fig. 2. Tests also confirm the ability of the robot in going up and down stairs and on an inclined surface of 28 degrees. Over a smooth surface (painted wood, a very slippery surface), the robot sometimes slips if it has to start on the slope or if it is climbing at low speed (0.35 m/s). This is observed using the tracks or the wheels. If AZIMUT starts at the bottom of the surface at a speed of about 1 m/s, or if the surface is changed to make it more adherent, then the robot has no problem climbing. The adherence of the diamond-shape tracks on stairs and other surfaces is very good.

Figure 17 presents two pictures of an articulation, one on a floor and the other on a stair. On stairs (0.178 m high and 0.279 m depth), we can notice that with the tracks not stretched or rigid enough, the robot has more difficulties climbing over the stair at low speed because of the small hole between the plate beneat the track and the wheel of the robot. Solutions for this problem consist of extending in the panel supporting the track and decreasing the radius of the wheel.

Note that we were not able to do a complete set of tests for the platform. This first prototype of AZIMUT is evaluated to be functional at 80% of its locomotion capabilities, which is very well considering the complexity of the design and the constraints in time, budget and resources. It was therefore not possible to validate that the robot can climb over obstacles of 250 mm, tests with various types of stairs and steep slopes (up to 40 degrees). While it was possible to come close to the desired specifications for the width, the height, the body clearance and the articulation blocking torque, the first prototype is heavier than expected. Table 1 presents such comparisons. Because of time and financial constraints, the chassis of the robot had to be made using

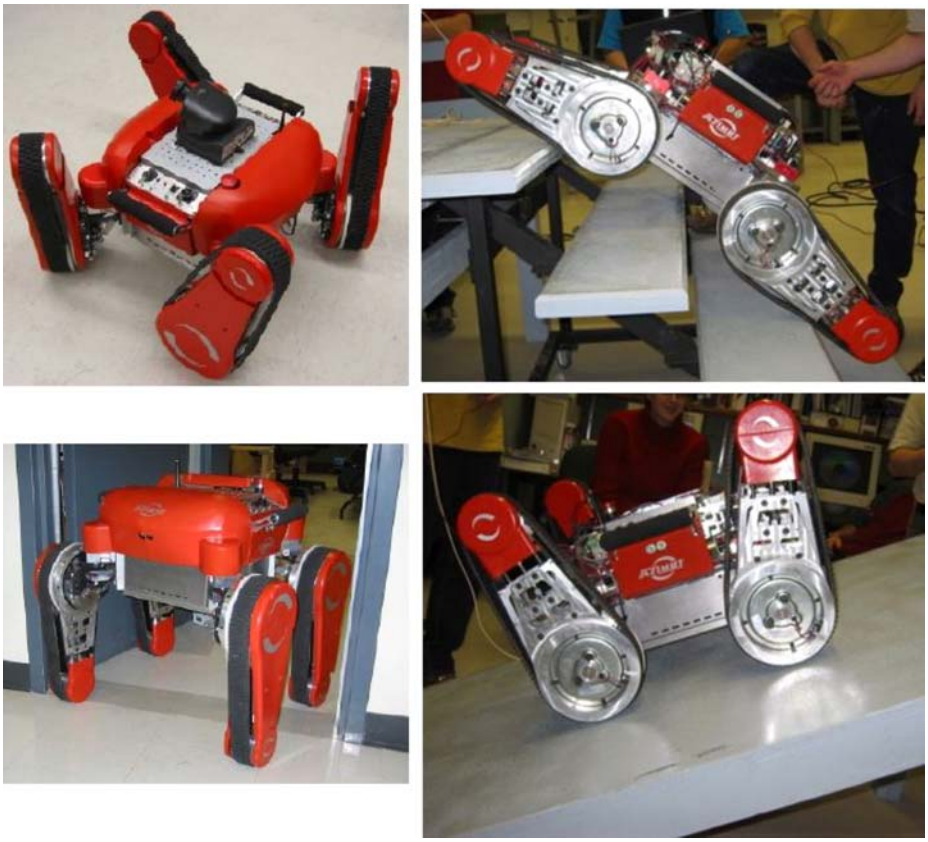

Figure 15. AZIMUT with its articulations in different positions (top left), on stairs (top right), going through a door (bottom left), and on an inclined surface (bottom right).

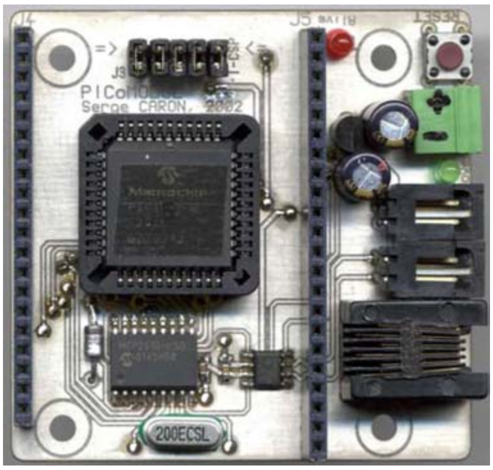

Figure 16. PICoMODUL board.

aluminum and steel parts without weight optimization. Using composite material to build the chassis would reduce the weight of the robot. As indicated earlier, the articulation lifting torque is lower than what we evaluated using the motor specifications (which revealed to not be completely accurate) and the mechanism designed. Reducing friction on the rotational joint of the articulation and improving the efficiency of the articulation gearbox (by replacing the worm gears for instance) would also improve quite a bit the lifting capability of the robot. This, combined with the increased weight, explain why the first prototype cannot lift itself up. Also, because of cost, availability and size issues, instead of using absolute encoders we had to select relative encoders for measuring the direction and the rotation of the articulations, and placed limit switches for calibration. For the rotation of an articulation, a single optical limit switch is activated when the articulation is in the vertical position. For direction, mechanical limit switches are placed to detect the limits of the motion range (-90 and 90 degrees). At startup, the articulations are set to move to activate these limit switches, allowing to reset to zero the positions derived from the relative encoders. Absolute encoders would not require to initialize the directions and rotations of the articulations

Table 1. Comparison between AZIMUT's desired and real specifications.

Specifications	Desired	Real
Length	68.6 cm	70.5 cm (119.4 cm articu. stretched)
Weight	54.4 kg	63.5 kg
Width	68.6 cm	70.5 cm
Height	35.6 cm	38.9 cm 66 cm (articu. down)
Body clearance	7.6 cm	8.4 cm 40.6 cm (articu. down)
Articulation lifting torque	96 N.m	26.4 N.m
Articulation blocking torque	96 N.m	88 N.m
Articulation direction torque	7.5 N.m	25 N.m
Propulsion encoders	1024 relative	1024 relative
Direction encoders	1024 absolute	1024 relative, with calibration sensors
Rotation encoders	1024 absolute	1024 relative, with calibration sensors
Maximum velocity	1.5 m/s	1.2 m/s (4.3 km/h)

Figure 17. Closer views of the articulations on the floor (left) and on stairs (right).

at startup. Finally, the velocity is measured on a flat surface and at 50% motor capacity. The maximum velocity is reasonably close to the desired value since in our tests we limited the power to the motors for safety reasons (we did not have any replacement motors in case of problems).

Concerning energetic autonomy of the platform, it all depends on the movements made by the robot and the inclination of the surface it is moving on. Theoretically, we evaluated that the robot would consume 6.25 A on flat surfaces and 17.9 A climbing over a surface. If we evaluate that it will encounter flat surface conditions 95% of the time and inclined surface 5% of the time, the average current required is 7.5 A. AZIMUT's battery packs can deliver 17 A.h, providing 2.25 hours of energetic autonomy. Practically, we observe more than 3 hours of energetic autonomy during trials done 70% of the time on flat surfaces and 30% of the time on inclined surfaces.

Finally, all tests were done using either direct commands of the articulations or the use of preprogrammed configurations of the articulations. Given the fact that the robot was not completely functional, it was not possible to validate autonomous modes of locomotion of AZIMUT. However, we noted that having 12 DOF, it is hard even in teleoperated mode to control the transitions of positions of the articulations under various constraints (not having the articulations interfere with each other, physically and with their directions). One possibility is to use specific articulations for direction and propulsion, making the robot controlled just like conventional platforms. Another solution is to add sensors measuring the forces on the joints of the robot and the effect of the shape of the environment. Such information, along with data taken from proximity sensors located on the robot and its onboard inclinometer, would then be useful to go to preset positions of the articulations in order to reposition the articulations in the most appropriate manner. A more interesting capability would be to use algorithms that allow to search for the appropriate transitions according to such data, minimizing displacement of the articulations while ensuring the stability and security of the robot. We do not have specific answers yet for these questions, but AZIMUT's locomotion capabilities will create opportunities to design novel active control functions in order to make it autonomous. Before working on that however, we need to demonstrate that the robot's locomotion capabilities can be fully implemented on a real platform.

6. Design Challenges and Methodology

Designing sophisticated mobile robot platforms is not an easy task but it is a necessary one if we want mobile robots to eventually become useful and efficient agents in our world. If we assume mobile robots are going to be used only over smooth surfaces, then perception is probably the most limiting factor to make them autonomous in their decisions. But since we live in a three-dimensional world, sophisticated locomotion capabilities are required. We started this project with little experience in designing highly sophisticated mobile robotic platforms. By facing the challenges of designing and building the first prototype of AZIMUT, we learned a lot on the different considerations that must be addressed, and the objective of this section is to report the conclusions derived from this experience.

As described in the previous sections, the design of a mobile robot such as AZIMUT involves many dimensions and tools, all required to successfully build a robot. No integrated tools or detailed methodologies exist to assist in the design process of a mobile robotic platform. For designing AZIMUT we used SolidWorks for technical drawing, Nastran for mechanical simulation, C compilers for PIC and nanoMODUL programming, a compiler for PDA programming, and other tools we had to design ourselves (like the simulator). Having described the design of one such platform, it is hard to imagine overcoming the complex engineering issues without following a detailed and structured design process, or without involving a team of people with various expertise and backgrounds.

The design process followed is based on concurrent engineering principles (Ulrich and Eppinger, 2000). These principles call for a strong requirement analysis over the entire life cycle of the product. This assures that the majority of the requirements and constraints are addressed early in the design process in order to minimize reengineering of the design later on. The methodology has six general phases: (1) Requirement analysis (identify user's need, operating conditions, projects constraints), (2) Functional analysis (transposition of the requirements into functional terms so that they can be organized and analyzed), (3) System design (elaborate and analyze general concepts addressing the identified functions), (4) Preliminary design (elaborate and analyse specific concepts for the different subsystems of the general concept selected), (5) Detailed design (for each subsystem, calculations, drawings, schematics and technology choices are made to produce the prototype), (6) Integration and validation (assemblage of all of the parts and test according to the requirements and functions).

When concurrent engineering approach is applied to a project involving a multidisciplinary effort, the difficulty it to be able to integrate early on a variety of fields of expertise, each with their own sets of constraints and design methodology. AZIMUT's design requires the integration of expertise in mechanical engineering (structural and part design, mechanical joints, weight estimation, calculation of torque and forces, assemblage of parts of the robot), in electrical engineering (batteries, power distribution, motors, encoders, sensors, wiring, heat dissipation, drives, controllers, circuits and computer boards), in computer engineering (processing capabilities, communication protocol, I/O interfacing, user interface, control of actuators, decision-making and debugging software) and in industrial design (aesthetic aspects such as color, bodywork design and construction). All of this must be done with strong considerations of the operating conditions (which include the environment, the users, the capabilities required in the field, etc.), and influences directly the choices to be made for efficient usage of the robot to be developed. From the continuous exchanges between specialists in such fields throughout the project, two important design compromises seem to be more critical:

- Energy vs Weight vs Torque. A mobile robot has to carry its own power source. For a mobile robot powered by electricity, batteries are an important part of the overall weight of the platform. This influences the torque that the motors must generate to make the platform moves (and lifts it up in the case of AZIMUT). The amount of torque influences the size and the energetic consumption of the motors, closing the loop regarding the interdependencies of these factors.

- Size vs Electronics vs Heat Dissipation. The size of the robot affects the amount of space available for the onboard circuitry and wiring of the robot. Minimizing size allows reducing the weight of the robot, but also decreases the amount of space left for the electronics. This also complicates heat dissipation for the circuits.

Adopting a rigorous design methodology is therefore very important to assess the risks and to monitor the progress in the design. But because a mobile robot is made of so many different components, an iterative design process must be followed: choices of components must be made, plans must be revised, small prototypes must be developed. As the concept evolves and the robot is constructed, the focus shifts from mechanical concerns to electrical, computer considerations and and design constraints. A full loop between the five domains must be completed at each phase of the design methodology, before moving into a new iteration of the design process.

Having historical data on the different elements that affect these compromises greatly help to optimize the different criteria. But since AZIMUT was our first design at this level of complexity, we did not have access to such data. Eventually time runs out and final choices must be made to start the construction of the robot. The design team may not always have the resources or the knowledge (for instance some parts may have incomplete specifications) to make the right choice or to use the proper part, and the final design decisions are not easy to make. The overall influences of these decisions can only be seen during the integration phase. Integration of all of the components is the real test to evaluate the design, and its is only then that the result of the design can be seen. During integration, the actual use of the robot as controlled by its software elements can give good indications on limits and improvements of the mechanical and electrical elements. The value of the integration phase and the time allowed to do it are usually underestimated. It should be clear though that they would be proportional to the number of elements to integrate and their respective complexity.

With all the difficult challenges to overcome when designing a mobile robotic platform, it is extremely hard to come up with a perfect design with the first prototype of a complex and new concept of a robotic platform. The main objective of the first prototype is to demonstrate the feasibility of the concept and to outline integration issues. There is much value gained in this process. To facilitate this iterative process, our design experience with AZIMUT reveals two major issues that we need to work on in the future for the design of sophisticated mobile robotic platforms: proposing a design methodology with tools specific to mobile robots, and adopting a modular design approach. We do not have a solution clearly outlined yet, but one idea is to derive a Product Architecture (Ulrich and Eppinger, 2000) that integrates all types of expertise. To achieve this goal, the Functional analysis would have to be built in a functional structure that highlights, between every function, all the flows of matter, energy and data that are used or transformed on the robotic platform. Grouping the functions in a fashion that minimizes the flow between the modules would allow determining the subsystems. It is easy to imagine that a Matter flow would be related to the mechanical components of the robot and the Data flow would be associated with algorithmic issues. As for the Energy flow, depending on technology choices (e.g., electric or hydraulic), it could be separated between mechanical or electrical considerations. The industrial design sets requirements on the geometric adjustments of the subsystems. Choosing subsystems that minimize the interfaces (flows) between each other is the key to an optimal modular design. It also considerably reduces the time needed for the integration phase. This functional structure would then be a common starting point for all the designers. To keep track of the interrelations between the subsystems and their parts during the design process, several graphic tools (flow charts, organization trees, 3D assembly design) would be needed to outline every interrelation between the subsystems in terms of flows (matter, energy and data), geometrical layout and control sequences, at every phase of the process. Requirements and specifications would be identified for each interrelation, addressing mechanical, electrical, computer or industrial design considerations depending on which type of flow they are associated with in the functional structure. This tool would provide a mean to quickly identify conflicts between the subsystems (or modules) and the compromises to be made between the different fields of expertise.

One outcome of this would be to come up with a set of mechanical-hardware-software-design components that can be reused in multiple types of designs, robotic or not. Such components could also be modeled in simulations and animations used by considering the physical limitation of technologies, to illustrate the proof-of-concept before starting the construction of prototypes. This is another reason why we adopted early on a modular design approach with AZIMUT. By developing modules for mobile robots, it is possible to isolate a desired functionality that can be tested, documented and reused on other designs. Since technological advances directly affect the design of mobile robots, following a modular approach is important to facilitating continuous improvements of the platform over time. Having such modules, it is therefore easier to focus on particular aspects of a design project, reexploit modules and upgrading them when necessary, instead of always having to start everything from zero. It also increases the robustness and the reconfigurability of the system. In AZIMUT, modularity is preserved at the structural level by putting the electrical and embedded systems inside the body of the robot, and by placing the actuators on the locomotion parts (i.e., the leg-track-wheel articulations) so that they can easily be replaced (by similar articulations or just some distinct locomotion modalities). Each controllable part of the robot is equipped with its own driver board and microcontroller board (selected according to the subsystem to control), distributing the control over the different subsystems of the robot. The challenge is to come up with the appropriate sets of modules. For that, doing a project like AZIMUT is a good starting point, since the robotic platform integrates many functionalities. Using these modules on other design projects also reveals to be an efficient test of the appropriateness of the module, and will help in refining the design methodology we hope to develop for mobile robotic designs.

7. Comparison of AZIMUT with Similar Robotic Platforms

Even though we came up with many solutions on our own, a lot of ideas from other robotic platforms exist in AZIMUT.

For instance, AZIMUT is capable of changing the orientation of its articulations, like four-wheel steering vehicles (Wang and Qi, 2001) and the NASA's Nomad robot.[2] The NOMAD has a transforming chassis capable of deploying its four wheels, enabling skid steering as well as explicit steering and increased stability.

While AZIMUT is much smaller than the Nomad (1.8 meter square to 2.4 meter square) and the WorkPartner (1.2 meter square) (Halme et al., 1999; Ylonen and Halme, 2002) robots, it is heavier and more complex to control compared to Rocky 7 (0.61 m × 0.49 m × 0.31 m, 11.5 kg, 6 DOF), Shrimp (0.6 m × 0.35 m × 0.23 m, 3.1 kg) or Urban robots. The cost in weight might be compensated by the versatility of the locomotion modes. For instance, with its tracks deployed the Urban robot (0.88 m (articulation stretched) × 0.4 m × 0.18 m, 20 kg) might have difficulty climbing a circular staircase, while AZIMUT will more easily do so by reorienting its articulations. We also evaluate that we could reduce the weight of AZIMUT by at least 20 kg (by using different materials for the structure of the robot and optimizing the amount of material used) in building a second prototype, learning from the results obtained with the first prototype.

WorkPartner differs from AZIMUT by putting wheels at the end of four legs, but the robot also has 12 DOF. Each leg of the WorkPartner robot has its own Siemens 167 microcontroller, which is similar to what we used, and the computer system is also distributed around a CAN bus protocol. WorkPartner is much more heavier (160 kg with 60 kg of payload) than AZIMUT, and the legs on WorkPartner cannot change their orientations as in AZIMUT. AZIMUT would therefore provide more flexibility in the locomotion modes. Using its wheels, WorkPartner can reach a speed of 7 km/h. The robot has a hybrid power system, which consists of a 3 kW combustion engine and batteries, and so it would be mainly used for outdoor applications. AZIMUT only uses electric power system and is targeted for indoor use (regarding size constraints).

Compared to Octopus (0.43 m × 0.42 m × 0.23 m, 10 kg with 5 kg of payload) (Lauria et al., 2002) robot, AZIMUT also uses PIC to distribute processing across the robots subsystems. Octopus uses however a master-slave configuration and exchange information using standard I2C protocol.

The concept closest to AZIMUT is the High Utility Robotics (HUR) Badger (Digney and Penzes, 2002). The HUR-Badger concept is derived from an analysis of what kind of locomotion capabilities a mobile robotic platform would need to follow a human soldier in an urban combat scenario. The design they came up with is made of two tracked units connected to a common body using rotational joints. The tracked units are sized such that they can be rotated through each other. By simulating in Working Model[3] the operational modes of the robot, they were able to demonstrate how the platform could be used in various configurations that would be necessary in real operational conditions. For AZIMUT, the target was for indoor environments like homes and offices. But AZIMUT validates with a real prototype the concept of leg-track articulations. AZIMUT's articulations can be made to work in pair-units instead of independently, and placed on an unsymmetrical base, coming close to create a first implementation of the HUR-Badger concept.

8. Conclusion and Future Works

In this paper we presented AZIMUT, a mobile robotic platform with four independent leg-track-wheel articulations. The concept is oriented toward making a robot capable of versatile motions and to negociating difficult three-dimensional obstacles such as stairs. The underlying strategy is that since there is no optimal mobility approach for all situations, AZIMUT tries to combine legs, tracks and wheels on the same platform. The first prototype confirms AZIMUT's potential for such capabilities. Also, while it was designed with indoor environments in mind, the concept can be adapted and be quite useful in outdoor settings.

We also outlined what we have learned from this design experience by describing the challenges faced and the considerations that reveal to be important during the design of the first prototype of AZIMUT. Integration of technologies and expertise is a fundamental challenge when designing a sophisticated mobile robotic platform. This first experience in designing AZIMUT provides interesting clues on integrated design tools to help in making complex mobile robotic platforms. In future work we hope to be able to develop and refine such tools.

This project also opens up new research issues not yet addressed with the first prototype such as distributed control of the articulations and perception in three-dimensional environment for navigation and for obstacle avoidance. We will continue working with this first prototype to explore further the various capabilities of the robot such as the autonomous four-wheel-steering locomotion control modes, active perception derived from sensors embedded on each articulation and the measurements returned by the inclinometer in the various locomotion modes of the robot. In the near future we hope to be able to build a second prototype, correcting the limiting factors of the first and demonstrating the full capabilities of the concept.

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Notes

1. http://www.cs.cmu.edu/trb/goat
2. http://www.frc.ri.cmu.edu/projects/meteorobot/Nomad/Nodam.html
3. http://www.krev.com/

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