Upgrading a Legacy Outdoors Robotic Vehicle[4]

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Abstract. ATRV-mini was a popular, 2000's commercially available, outdoors robot. The successful upgrade procedure of a decommissioned ATRV-mini is presented in this paper. Its robust chassis construction, skid steering ability, and optional wifi connectivity were the major reasons for its commercial success, mainly for educational and research purposes. However the advances in electronics, microcontrollers and software during the last decades were not followed by the robot's manufacturer. As a result, the robot became obsolete and practically useless despite its good characteristics. The upgrade used up to date, off the shelf components and open source software tools. There was a major enhancement at robot's processing power, energy consumption, weight and autonomy time. Experimental testing proved the upgraded robot's operational integrity and capability of undertaking educational, research and other typical robotic tasks.

Keywords: all terrain autonomous robotic vehicle, educational robotics, ROS, robot upgrade, solar panels.

1 Introduction

This work deals with the upgrading procedure of a decommissioned Real World Interface (RWI) ATRV-mini all-terrain robotic vehicle. The Intelligent Systems and Robotics Laboratory [1] purchased two ATRV-mini robots in 2000. The robots were fully operational for more than 5 years taking part in several research and educational projects [2,3,4,5,6]. The experience gained from these projects, highlighted two main points regarding robot's operation:

- Its energy reserves proved to be inadequate for its operational needs. Battery life in a typical testing scenario, where the robot is on the move for

[4] This work was funded and supported by the Graduate Program at the School of Production Engineering and Management of the Technical University of Crete, Hellas

Fig. 1. The *reDevil* robot: an upgraded ATRV-mini outdoors robotic vehicle.

approximately 20% of its total operating time, was less than the 3 hours period advertised by its manufacturer.
– Some of its hardware components, like the hard disk drives with moving parts, made it prone to failures because of the heavy vibrations being present during outdoors use. This fact resulted to frequent unexpected program terminations leading to serious problems during code debugging or experimental testing.

On top of the above mentioned issues the robot was decommissioned because of the following reasons:

– the electronic components reached their end of life and
– developing, upgrading or updating its software was prohibited by its outdated hardware's limitations.

However, the robot's mechanical design, construction and parts are robust and rugged, even with nowadays criteria, Fig. 3. Its dimensions, frame, wheels, electrical motors, and transmission are not just fully functional but also seem ideal for a modern outdoors robot, Table 1. Inspired by the fact that the mechanical parts of the ATRV are not obsolete at all, this paper describes the electronic components replacements in way that assumes the operational use of the robot for nowadays use. Almost twenty years after its purchase the ATRV-mini was upgraded so as to take advantage of its mechanical design, confront its cons and bring its electronic equipment back to *life*. The upgraded robot is now called *reDevil*. The basic criteria for choosing the components and selecting the software tools and modules, to be used for installation or development, were:

– the low *cost* for purchasing each hardware component and also the low *cost* for the support and maintenance.
– *open source* philosophy, as it offers several development benefits, such as: potential for full customization, modularity along with the ability to use

Table 1. ATRV-mini specifications

Specification	Value
Dimensions	62×53×45cm (L×W×H)
Clearance	7.62cm
Body	Formed & welded aluminium
Speed	1.5m/sec
Payload	9kg
Drive	4 wheel
Steering	skid steering
Turn Radius	Zero, turns on centre
Tyres	25.4mm pneumatic knobby
Motors	2×0.10HP, 24V DC servo

already available resources, on site maintenance opportunity and capability for diaphanous system's modules integration. Drawbacks, like the lack of support and reliability, are effectively controlled by the heterogeneous expertise and the extroversion found at the Internet resources of the open source community.

The upgrade procedure consisted of the following steps:

1. Market research and new hardware design,
2. hardware components replacement,
3. software development and
4. field testing.

During the reconstruction the mechanical parts and design remained intact. In the contrary, robot's electronic components were replaced with up to date, off the shelf components.

Although there are several works referred to the design and development of prototype robotic vehicles, ROS powered[7,8,9] or not [10,11,12,13,14,15], still there are no works relative to the upgrading procedure of decommissioned autonomous robotic vehicles.

The paper has the following structure: the upgrade procedure is described in Section 2, while Section 3 refers to the software development onboard the newly installed robot's hardware. The results of the reconstruction are presented in Section 4. Section 5 and 6 include the cost analysis and the conclusions of the project respectively.

2 Reconstruction Procedure

2.1 Controller

The robot's original electronics configuration was based on a RedHat Linux [17] powered Pentium III computer system [16]. The manufacturer provided

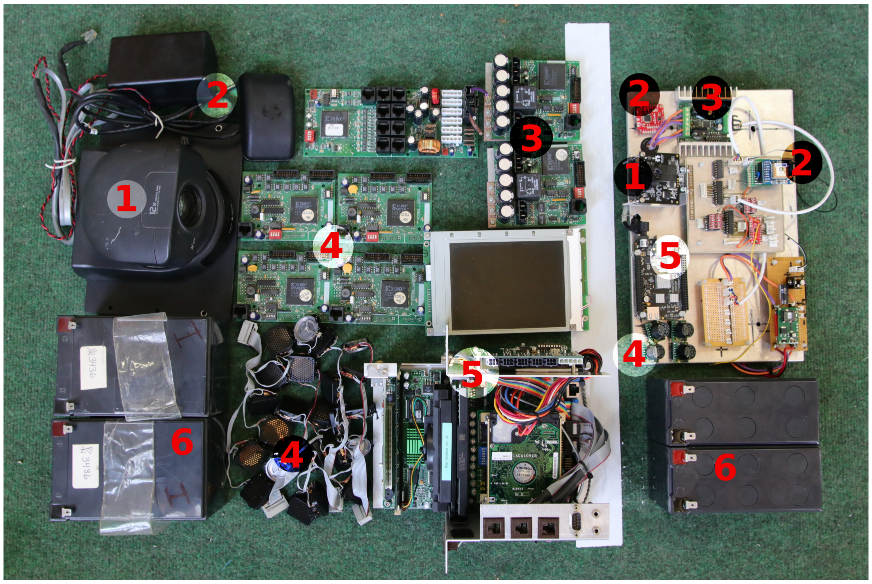

Fig. 2. On the left and the right of the white line is shown the electronics equipment before and after the upgrade: (1)cameras, (2)orientation sensors, (3)motor drivers, (4)ultrasonic sensors, (5)controllers and (6)batteries.

a software module called *Mobility*, to cover the necessity for an Application Protocol Interface (API) useful for the development of custom robotic controllers and the access to robot's hardware resources. Mobility was an object-oriented framework consisting of software tools for programming in Java or C++ and accessing robot's devices such as motors and sensors. Code development was simplified as it was a successful software layer between the user applications and the robot. In addition, the robot was equipped with the rFLEX system, a module dedicated to motion control and diagnostics.

The rFLEX system was removed while the Pentium III Mobility system was replaced with an Ubuntu [18] *Robotic Operating System* (ROS) [19] powered BeagleBone Black (BBB) single board computer [20]. BBB is an open source, ARM based development platform with adequate processing power and input-output ports for controlling an outdoors robotic vehicle. The BBB's 4GB 8-bit eMMC on-board flash storage counterfeits one of the original ATRV's design main disadvantages: the frequent unexpected program terminations due to the use of a hard disk drive unit which, as stated before, was prone to the heavy vibrations being present during outdoors use.

2.2 Sensors

Ultrasonic Sensors. ATRV-mini in its original configuration was equipped with 24 ultrasonic sonars. In each one of its four corners there were six sonars with a dedicated controller. The original sonars, including their controllers, were replaced with four ultrasonic range finders [21], three at the front part and one at the rear. This is an experimental initial configuration for obstacle detection, which may be easily expanded in a later time. The new sonars are self contained modules, directly connected to the BBB without the use of intermediate dedicated controllers.

Global Positioning System (GPS). GPS sensor was not described in detail in manufacturer's documentation. It was replaced with an Adafruit Ultimate GPS Breakout [22] featuring accuracy better than 3m and a refresh rate of 10Hz.

Inertial Measurement Unit (IMU). ATRV-mini was equipped with an electronic compass sensor that was replaced by a Sparkfun Razor 9 degrees of freedom IMU including 3-axis accelerometer, gyroscope and magnetometer [23]. Razor IMU is a tiny open source, multipurpose orientation module able to confront all the possible operational needs of an outdoors robot.

Camera. ATRV-mini sensors' suite included a Sony EVI D30 color pan-tilt-zoom video camera equipped with an automatic target tracking and motion detector. It was replaced by a Pixy CMUCam5 [24] a low cost, low power, open source, embedded color vision system designed for mobile robotics. The main reason for choosing Pixy was its ability to process images by its embedded microcontroller, able to manage speeds up to 50Hz, without consuming any BBB computational resources.

2.3 Motor Driver.

ATRV-mini was a skid steering robot equipped with two 24V motors including odometers. Each motor is driving, via a belted transmission system, a pair of wheels, as shown in Fig. 3. The reconstruction process did not alter this differential drive design. Yet, the original motor driver circuit was replaced with the Dimension Engineering Sabertooth dual 12A module [25], so as to be compatible with the rest of the new electronics. It is worth mentioning that this module is capable of regenerative braking and thus it enhances the robot's energy consumption.

2.4 Battery and Solar Charging System.

To confront with the problem of limited autonomy time, being the second of the original configuration's main disadvantages, the ATRV was equipped with a solar charging system. The system consists of three 8V-5.2W solar cells connected in series, resulting in an energy grant of 15.6W charging power in total, under direct sunlight. Although the solar panels' installation was the most expensive

Fig. 3. The reconstruction procedure left robot's frame, wheels, electrical motors, and transmission unchanged.

upgrade and increased the robot's mass by 1.5kg, yet this overkill was totally counterweighted by the improvement of the robot's autonomy regarding its energy reserves: the panels provide the necessary energy, during a sunny day, for totally covering the power demands of the robot's renovated electronics and sensors. When this is the case, battery power is reserved only for the robot's motors. After the electronic components' upgrade, the robot's energy consumption has been decreased considerably. This fact, in conjunction with the charging power added at the reconstruction, led in the decision of reducing the batteries' capacity. The original 2x12V-12Ah lead acid batteries were replaced by 2x12V-7Ah ones, leading to a total weight reduction of 2kg.

3 Software Development

Due to the replacement of the original Pentium III-Mobility module with the ROS powered BBB, a novel API should be developed. ROS is an open-source, meta-operating system specially designed for robotic applications [19]. It consists of tools, libraries and conventions that aid the development of robotic software. It is based on collaborative software development so that its ecosystem of tens of thousands of users worldwide can use each other's work in their projects.

To process reDevil's controller inputs a set of custom ROS *nodes* were programmed to access its sensor readings. As a result of the open source and collaborative character of ROS, there was no need to develop nodes for the GPS and Pixy camera modules, since they were already available in the ROS users

Table 2. Upgrade Enhancemets

Specification	Before	After
Weight	47kg [5]	40kg
Run Time	3-6hr, terrain dependent	4hr
Power Supply	2×12V-12Ah	2×12V-7Ah
Additional Power	none	3×5.2W Solar Panels
Motion Control	rFlex system	ROS control programs
Computer	Pentium III EBX	Beaglebone Black Rev.C
I/O Ports	Ethernet, Serial, Joystick	Ethernet, GPIO, I2C, A2D, Serial,
WiFi	802.11b	802.11n
Sensors	24 Sonars, Pan-Tilt Camera, GPS, Electronic Compass	4 Sonars, GPS, IMU, Camera,

community [26]. To manipulate the reDevil's controller outputs a custom ROS node was programmed to communicate with the motor driver and control the wheels' rotating speed and direction.

A part of the upgrade procedure was to develop a custom software framework to exploit the robot's potentials and prove its functionality. So, the following robotic algorithms and functions, typical in the area of outdoors robotic vehicles, were successfully implemented and tested as ROS nodes, in consecutive strands, using reDevil.

3.1 Remote Control Node

A console user interface was developed so that the user can remotely navigate reDevil. Apart from the navigation commands, the interface displays all the important information regarding the robot's operation, such as solar panels voltage, energy reserves level, geographic coordinates, linear and angular velocities, roll, pitch and yaw orientation.

3.2 Move to Point Node

After programming the *Remote Control* ROS node, the more complicated *Move to Point* node was developed, Fig. 4. The increased complexity is due to the navigation process, as there is no robot tele-operation at the *Move to Point* node and the navigation process should be programmed based on the GPS readings. *Move to Point* inputs are the coordinates of a target Point Of Interest (POI), to which the robot will move to and the orientation it should has there. This node was quite important as the majority of the next strands are based on this.

[5] Although according to the manufacturer's specifications the robot's weight was 38.5kg, still its actual value was measured 47kgs. The first value might was the robot's weight excluding its batteries.

Fig. 4. The experimental testing scenario for the *Move To Point* node was driving the robot from its current position X, straight to POI A, travelling a distance of 30m using half speed - approximately 5.2km/h. The path followed by the robot is shown in magenta. The mean error value, i.e. the distance from the straight path, was 0.8m and it is due to errors at the GPS readings.

3.3 Waypoint Movement Node

Moving between multiple POIs was the purpose of this node, Fig 5. *Waypoint Movement* is in fact repetitive and consecutive calls of the *Move To Point* nodes.

3.4 Object Following Node

The *Object Following* node was developed to utilize the robot's camera. The testing scenario included the following of an object of a destinctive color of user's choice. The target object was hand held and moved following a predefined path, passing through the positions A, B, C, D and E, Fig. 6. The robot was programmed to lock the predefined colored object in its camera's view and follow it.

4 Performance Enhancements

ATRV-mini was equipped with modern electronics, 17 years after its purchase. This upgrade led to certain performance enhancements, Table 2. Figure 2 shows the electronic equipment before and after the upgrade.

4.1 Energy Consumption

Robot's consumption in its original configuration was approximately 60W while idle. After the upgrade this consumption was reduced about 80%, leading to a

Fig. 5. The experimental testing scenario for the *Waypoint Movement* node was to move through the multiple POIs, A, B, C, D. The actual path followed by the robot is shown in pink. The experiment was conducted using half speed - approximately 5.2km/h. The path followed by the robot is shown in magenta. The mean error value, i.e. the distance from the straight path lines, was 0.8m and it is due to errors at the GPS readings.

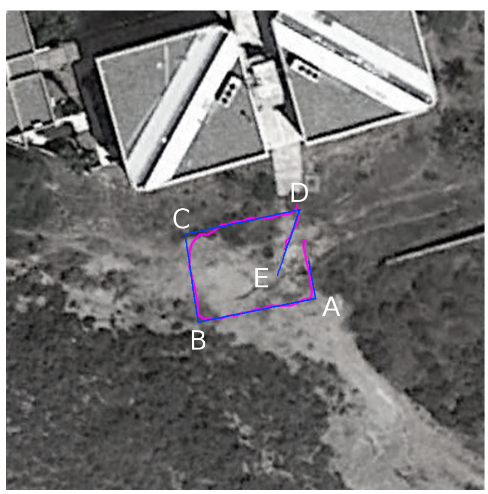

Fig. 6. The paths followed by the target color object and the robot, at the *Object Following* testing scenario, are marked blue and pink respectively. The errors are due to the hysteresis of the robot's locomotion system.

total consumption of 12W, even though there is a certain boost in the overall processing power. Indicatively, the 29W consumption of the original onboard laptop was reduced to 1.2W of the BBB in the current configuration.

4.2 Weight Reduction

The upgrade procedure resulted to a weight reduction of approximately 14%, even after the addition of the solar panels. The weight reduction resulted to a motor consumption decrease, described at the next subsection, although the propulsion system remained unchanged.

4.3 Operation Time

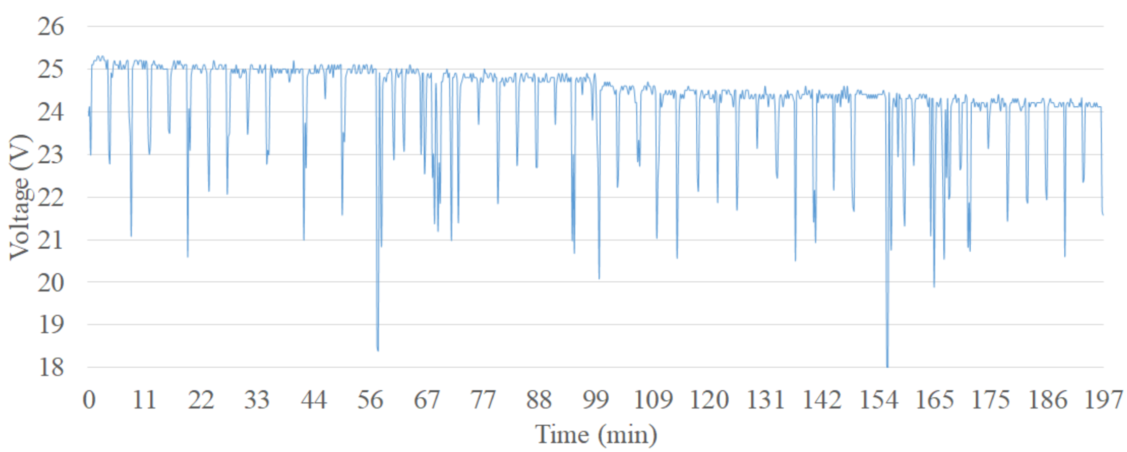

Fig. 7. The battery voltage during the consumption test. Three hours of typical outdoors operation resulted in a voltage drop of approximately 1V. The instantaneous voltage drops are due to robot's movements, where the consumption is many times bigger than when the robot is idle.

The enhancements above led to a notable operation time increase. This fact supported the decision of using reduced capacity batteries. Instead of the original 2x12V-12Ah, the lighter 2x12V-7Ah battery pack was used. This new configuration was tested under the following scenario: every three minutes a 20 meter distance was covered repeatedly between two POIs, A and B. After three hours of testing, the energy level was about 30%, Fig. 7, 8. This was a significant improvement compared to the original operating time of less than three hours, as stated before.

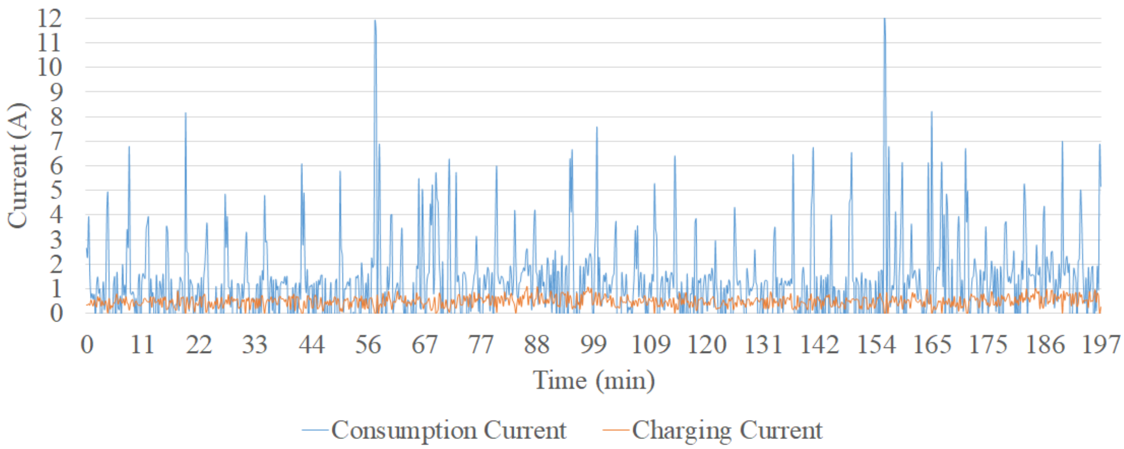

Fig. 8. The instantaneous consumption current's intensity peaks are due to robot's movements, where the consumption is many times bigger than when the robot is idle. The bottom diagram shows the instantaneous intensity of the consumption and the solar panel charging current.

Table 3. reDevil's electronics components cost.

Component	Cost in €[6]
BBB Controller	80
Motor Driver	95
Solar Panels	180
Solar Panel Charger	25
Ultrasonic Sensors	128
Batteries	36
USB Hub 4 port	20
USB WiFi	17
GPS module & antenna	77
IMU module	58
Camera	80
Power supply circuit	40
Custom PCBs	35
Total Cost	*871*

5 Cost Analysis

One of the upgrade procedure's requirements was the use of branded, off the shelf components, commonly used among the robotics community. The chosen products are worldwide available via a large number of e-shops and other retailers. Table 3 shows the cost analysis of the components used.

It's worth mentioning that the total cost of 871€ for the components used in the upgrade procedure does not exceed the 1000€ threshold. This amount is a fracture of the original equipment's cost. In early 2000s there was limited access to commercially available components designed specifically for robotic use. Moreover, the robot manufacturers of that time used to develop custom electronics solutions for their products, as there were limited options of choosing commercially available components. In the ATRV-mini robot the rFlex system, along with the motor and sonar controllers were dedicated products developed in house. Nowadays, there are plenty of e-shops specialized in selling robotic equipment in affordable prices offering great variety and support.

The project's open source philosophy led to a practically zero software development cost. For example, the costly Mobility software, included in the ATRV-mini original configuration, was replaced with the free of charge ROS implementation. The whole upgrading procedure was a complex task of approximately 250 working hours of development, construction and programming. Also, during the several steps of development, the laboratory and field tests that were conducted lasted approximately 250 hours.

6 Conclusions

ATRV-mini, a seventeen years old, retired outdoors robot, was reconstructed as reDevil, with up to date robotic hardware and open source software solutions. reDevil presented enhancements like increase of autonomy time, reduction of energy consumption and weight. The retired robot became fully operational after approximately 500 working hours, using components with a total cost of 871€.

After successful laboratory and outdoors experimental testing, reDevil proved to be adequate for undertaking the following tasks:

- *Education and Research*: may be used to engage students and researchers in robotic hardware or software projects, covering topics like real-time programming, reporting and visualizing experimental data, energy management techniques, sensor fusion, robotic vision, navigation-localization-mapping and multi robot teams. In fact, reDevil is already participating in several ISRL's educational and research projects.
- *Security and Surveillance.*

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- *Search and Rescue - Reconnaissance.*
- *Monitoring and Maintenance of buildings and structures.*
- *Agricultural monitoring.*
- *Fire Fighting.*

Future plans include the sensor suite enrichment along with the development of software packages supporting robot's autonomy. At least one forehead lidar ranging sensor and two additional ultrasonic sensors at each robot's side will support the future navigational tasks. Finally new software packages will be developed to fine tune and sustain robots energy autonomy. Thus, apart from navigation, localization and path planning future research will focus to maintain robot's energy reserves above a safety level, by programming and managing energy consumption, reconsidering and revising the robot's mission goals, as needed.

In 2000s robot building and programming was a privilege of high budget, state of the art companies or research institutes. Nowadays, things have changed as the access to robotic resources is incomparably easier and cheaper. From the other point of view the rapid evolution in robotic technology requires a constant effort to stay competitive and up to date.

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