The Design of Autonomous Mobile Unmanned Outdoor Research Robot

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Abstract **– The design methodology for autonomous mobile research robot is proposed. It includes four design stages. At the first stage, the cluster model of sensors and actuators is used to represent the structure of the robot, and the real-time analysis is performed at different periods of robot activity phases. To determine timeliness of the robot, two methods are used. With the help of the first method, the robot is determined as a hard real-time system, when all phases are defined as hard deadlines and executed sequentially. With the help of the second method, the robot is determined as a system having activities with hard and soft deadline execution times. Timeliness of the system is calculated using the time/utility function (TUF). At the second stage, hardware-software architecture is selected and estimated according to the real-time system analysis. At the third stage, the flexible robot physical model is developed and investigated. The fourth stage is devoted to the design of prototype.**

Keywords **– robot, real time, activity phase, sensor, actuator, physical model.**

I. Introduction

Autonomous outdoor robots designed for military and space applications have widely spread since the end of the 20th century [1][2][3]. At present, unmanned autonomous outdoor research robots help solve different tasks applied to agriculture, urban utilities and hard environment dangerous for a man.

A variety of ready-made research robots (Seekur, Phoneer3-AT, Phoneer3-DX, SegwayRMP400) are used primarily by researchers. Unfortunately, because of the cost of these systems they are not widely spread and remain inaccessible to educational institutions and individual enthusiasts. The design of a new mobile research robot for educational and training purposes is topical.

Before conducting the commercial research on the design of an autonomous robot for unstructured environment, it has been necessary to solve different significant problems: position estimation, obstacle avoidance, motion planning and map building, time and energy consumption estimation [4].

Different robot design steps and methodologies are proposed in literature. One of the methodologies has three key stages for the design of a robot for civilian purposes [5]. At the first stage of design process, the number and type of necessary sensors and actuators are determined. The second stage requires an assembly of working prototype. The third stage involves the testing of robot's ability to work in a group.

There is also methodology, which proposes a six-stage design: 1) problem definition; 2) research; 3) brainstorming; 4) the design, test and evaluation of the best solution; 5) building of a model; 6) building of a prototype [6].

For example, the 10-stage design methodology, which is proposed in [7], starts with the setting of a problem statement and ends with implementation, testing and manufacturing.

The methodology proposed in this article is not devoted only to the design of some specific autonomous unmanned outdoor robot. It can be used to solve different problems concerning the development of mobile research robot solutions.

Taking into account the above-mentioned facts, it is clear that time consumption of the research robot is application dependent.

The first stage of the proposed methodology is devoted to the determination of task independent time consumption of the developed robot at the design stage as well as of the existing ready-made robots.

At this stage, the robot is proposed as the embedded cluster network of sensors and actuators; its real-time analysis is estimated and timely analysis is performed. At the second stage, hardware-software architecture of the research robot is discussed, selected and optimized. At the third stage, a physical model of the robot [8] is built. At the fourth stage, the prototype of the robot is built and investigated.

II. The Mobile Robot as an Embedded Real-Time System

The autonomous robot is proposed as the embedded cluster network of sensors and actuators (Fig. 1). Its general structure includes:

- $M = m_a + m_b + m_c$ sensors se_{im} processing signals received from environment;
- se_{1ma} sensors connected directly to CPU (section *a*);
- sensor nodes $se\text{-}node_{ji}$ collecting data from sensors, and converting it in a way used by CPU (section *b*);
- interfaces if_j transferring data from sensor nodes $se\text{-}node_{ji}$ to CPU;
- $N = n_c + n_d$ actuators ac_{in};
- interfaces if_j transferring data from CPU to $ac\text{-}node_i$ nodes;
- $ac\text{-}node_i$ nodes required to convert digital data received from CPU to analogue signal controlling actuators;
- $se\text{-}ac\ node_i$ for sensor signal acquisition, actuator control, data collection and transfer to and from CPU in time t_{di};
- interfaces if_j transferring data from and to CPU to $se\text{-}ac\ node_i$ nodes in time t_{cfi};
- node $node_f$ connecting database DB, GPS and external control system HUM to CPU.

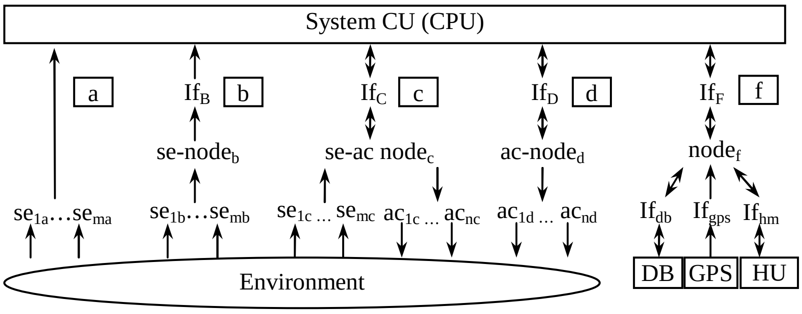

Fig. 1: General structure of the autonomous mobile robot. CU – Calculation (Control) Unit, If – the data transfer interface, se – sensors, ac – actuators, DB – Database, GPS – the navigation system, HUM – the manual control system.

TABLE I

VARIABLES DESCRIBING TIME DELAYS GENERATED BY DATA TRANSFER AND PROCESSING

	a	**b**	**c**	**d**	**f**
CU	$t_{CPU\ a}$	$t_{CPU\ b}$	$t_{CPU\ c}$	$t_{CPU\ d}$	$t_{CPU\ f}$
If_j		$t_{if\ b}$	$t_{if\ c}$	$t_{if\ d}$	$t_{if\ f}$
Node		$t_{nd\ b}$	$t_{nd\ c}$	$t_{nd\ d}$	
se; ac	$t_{se\ ai}$	$t_{se\ bi}$	$t_{se\ ci}$, $t_{ac\ ci}$	$t_{ac\ di}$	

Activity execution phases of the unmanned outdoor robot are represented by $N+1$ states of main finite automata and different execution time intervals – phases T_0, T_1, …, T_k, …, T_N. Phases k can include particular phases or a number of N_k states and execution cycles or activities t_{kw}. Execution cycles at particular phases can be performed concurrently or sequentially.

At *phase zero* (time interval T_0), configuration data is loaded to registers of nodes according to the main program. This program can be held in ROM of the central unit or loaded using wireless connection from the user database. It is not necessary to include phase zero in the estimation of real-time characteristic of the autonomous mobile outdoor robot.

At *phase one* (time interval T_1), the robot estimates the surrounding environment and builds the route map.

This phase includes the following activities (labelled T_{11}): horizontal turning to the left to the start point of camera turret using servomotors (t_{CMtn}), robot start point coordinate estimation using GPS (t_{GPS}), data acquisition from digital compass (t_{CMP}), recalculation of the robot position and start point coordinates, data processing by CU in time (t_{CUst}).

At this point, data acquisition from GPS and digital compass can be executed simultaneously, at the time required to turn the camera turret.

At T_{12}, the camera turret turns both in horizontal (t_{CMh}) and vertical (t_{CMve}) directions using servomotors, processes the images received by the camera (t_{CMvi}), measures the range to the object by optical infrared short range (t_{RMS}) and long range (t_{RML}) finders. This process can be repeated as many times N_{1tm} as necessary to investigate the available view sector.

The sum of activities, in this process, can be expressed as follows:

$T_{12} = N_{1tm}(t_{CMh} + t_{CMve} + t_{RMS} + t_{RML} + t_{CMvi})$

Under optimal conditions, one iteration of this process is necessary

$N_{1tm} = 1$

T_{13} represents the second object search N_{2tm}

$T_{13} = N_{2tm} (t_{CMh} + t_{CMve} + t_{RMS} + t_{RML} + t_{CMvi})$

The last activity made at phase one is the calculation of the route map in time t_{CUrmp} using the data collected earlier.

The time spent to perform actions at phase one can be calculated using the following formula:

$T_1 = T_{11} + T_{12} + T_{13} + t_{CUrmp}$

To make application independent evaluation and comparison of different mobile autonomous robots, 5 major action phases of the robot have been selected:

Phase one (time interval T_1) – estimation of the environment and building the route map;

Phase two (time interval T_2) – robot turning to the required direction controlling its motors;

Phase three (time interval T_3) – robot movement by the calculated route map;

Phase four (time interval T_4) – the investigation of object parameters;

Phase five (time interval T_5) – obstacle avoidance.

Execution time for each deadline can be calculated. The sum of all execution times of all phases sets $WCET_i$ (worst-case execution time) – hard deadline d_{hi}. With it the robot is determined as a hard RTS (real-time system).

$$\sum\nolimits_{T_i}^{5} = T_1 + T_2 + T_3 + T_4 + T_5; \qquad (1)$$

$$\sum\nolimits_{i}^{5} WCET_i = D_h; \qquad (2)$$

For the generalized analysis with hard and soft execution time, the time/utility function (TUF) can be used. Generalized timeliness calculation meter “time/utility function (TUF)” was proposed by Professor E. D. Jensen in 1976. TUF is a generalization of the deadline constraint, specifying the utility

(U) to the system resulting from the completion of an activity as a function of its completion time.

Quantitative evaluation of the real time is the sum UA of TUF UA_i [9]:

$$UA = \sum TUF\ UA_i = \sum T_i; \qquad (3)$$

$$\sum_{T_i}^{5} = T_1 + T_2 + T_3 + T_4 + T_5 = D_S \le D_h; \qquad (4)$$

Remark. Phases four and five mentioned earlier in the text are task dependent and may not be included in time consumption estimation.

The complete analysis of time consumption and performance of the mobile robot physical model is proposed in publication [10].

III. The Development and Optimization of Robot Structure and Architecture

After estimating the time consumption of the system, it is time to develop the system architecture. At this point, it is possible to investigate the load on data bus nodes, CU and energy consumption of the robot. These parameters also affect time consumption of the mobile robot.

One of the effective ways to decrease energy consumption of the robot control system is to optimize the number of system nodes – one node can be used to transfer data for more than one sensor or actuator.

Load on CU can be decreased by using the distributed data processing system, where each node will perform some calculation tasks.

In some extreme cases, the system can use only one node or no nodes at all for all sensor and actuator connections (Fig. 2.)

Optimal solution is to keep balance between energy consumption and data processing performance according to the set task.

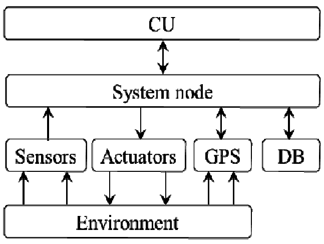

Fig. 2. Robot interconnection structure using one node

For example, the calculated time consumption for the first developed physical model after optimization has been:

$$\sum_{i}^{5} WCET_i = 23s = D_h; \qquad (5)$$

$$\sum_{i}^{5} TUF\ UA = T^1 = 19s = D_S \le D_h; \qquad (6)$$

During experiments two robot physical models have been developed. Main statements to develop these systems: during research a platform is often needed to perform algorithm tests and experiments. It should be able to act autonomously and execute operator commands. Also operator should be able to get information about the environment, in which the robot acts. The robot platform should be composed of modules, which could be used to build other robotic systems.

IV. The Physical Model of the Mobile Robot

At the third stage, the physical model of the mobile robot is developed and used for the experimental estimation of time, reliability, energy consumption and cost.

Hardware structure of the first physical model is represented in Fig. 3.

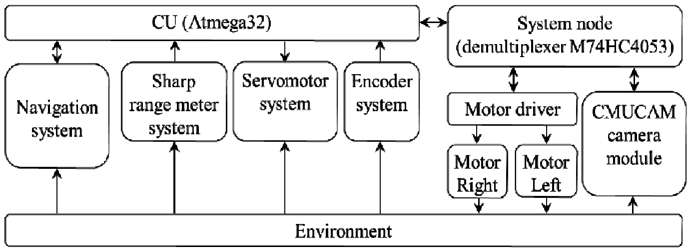

Fig. 3. Structure of the physical model

It has only one system node – signal demultiplexer M74HC4053 for the motor driver and camera module control. Other sensors (the navigation system including electronic compass CMPS09, the rangefinder system consisting of two rangefinders – Sharp GP2D15 and GP2Y0A710YK) are directly connected to the central unit. The physical model is able to execute the preprogrammed algorithm.

Fig. 4. External view of the physical model

Taking into account the results obtained after a period of trials and exploitation, a decision has been made to upgrade the physical model. Hardware architecture of the upgraded physical model is represented in Fig. 5.

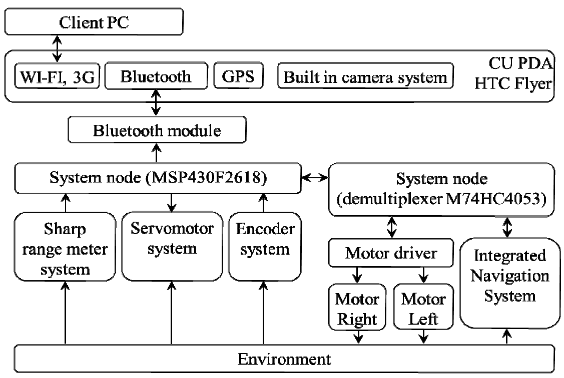

Fig. 5. Structure of the upgraded physical model

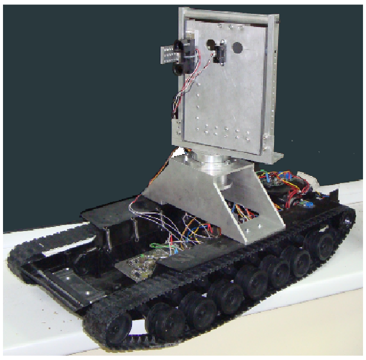

Fig. 6. External view of the upgraded physical model

As a central unit for the new generation autonomous mobile robot design PDA HTC Flyer has been used. It has been chosen because one of the authors has already had it. Also because of its powerful capabilities and processor, the HTC Flyer is capable to perform a wide range of tasks.

Hardware architecture has two system nodes: MSP430F1611 MCU, which collects data from robot sensors, such as rangefinders, encoders, controls servomotors and the second system node M74HC4053 signal demultiplexer with the help of which the robot motor driver system is controlled and data from the integrated navigation system is read. Both nodes are placed on one system board.

The system board provides possibility to use all MSP430F1611 MCU pins. This allows expanding the system easily.

The system board has 3 voltage supplies – 5V to feed 5V USART, drive rangefinders, motor drivers and additional sensors; 3.3V supply to feed MSP430F1611 controller, signal demultiplexer, additional sensors; 3V supply is used as a reference voltage for ADC part of MSP430F1611 controller.

Communication between HTC Flyer and MSP430F1611 controller is organized using the Bluetooth interface.

The robot is able to act in two modes. In the first mode, the robot acts fully autonomously using the programmed algorithm. In the second mode, the robot is controlled by an operator using terminal software running on PC or PDA.

Main differences between the first and second mobile robot physical models are the following:

- Video camera module. The first robot used CmuCam 3 developed by Carnegie Mellon University. It had some disadvantages, such as low image resolution, low data transfer rate, camera matrix low sensitivity to the red colour. New robot uses the built-in high-quality, high-resolution 8Mpix camera module. Since the camera module and system processor are placed on one module – HTC Flyer, the image data transfer and processing speed have greatly increased.

- Navigation system. For the navigation purposes, the first robot used the electronic compass CMPS09, encoder system, and rangefinders. New system uses the integrated navigation system containing Sparkfun 9DOF AHRS module and GPS. Sparkfun 9DOF AHRS module includes a 3-axis magnetic compass, 3-axis gyroscope, 3-axis accelerometer and ATmega328 for data processing and transfer purposes.

The adaptive filter (Kalman filter) Sparkfun 9DOF AHRS module helps make much more precise robot position and direction determination in comparison with an electronic compass.

Software architecture used to control the upgraded physical model includes 3 units.

Sensor data readout and actuator control unit running on MSP430F2618 provides the processing of the developed data transfer protocol, controls the motor driver, turret servomotors, reads and sends on-demand data from the rangefinder system, integrated navigation system.

Data conversion and communication module running on PDA HTC Flyer under control of Android OS controls the sensor data readout and actuator control unit, processes data received from sensors, processes image recognition algorithms, makes decisions on further actions. One of the additional modules developed in this unit is a server. It provides security system and telemetry data for terminal client software.

Third part – client software. It provides the robot control system and telemetry data display system.

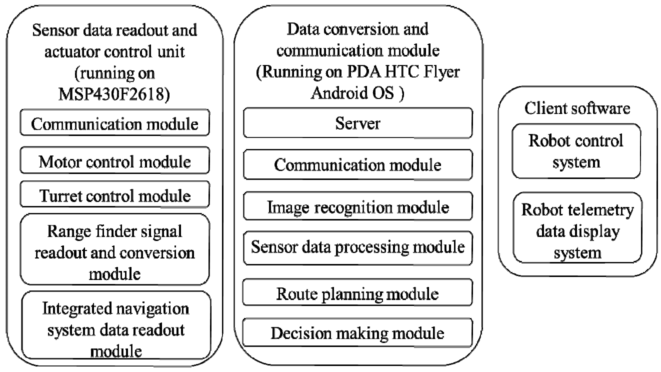

Fig. 7. Software architecture of the upgraded physical model

After developing and testing of software and hardware of the physical model, it is time to develop the prototype of the robot. It is the fourth stage, which our developed robot will pass though.

V. Conclusions

The methodology proposed in this article has been successfully used to develop the robot physical model.

It is able to act autonomously according to the preprogrammed algorithm or it can be driven by an operator connected to it over the Internet. Next stage is to develop a full size prototype of the mobile robot.

The robot physical model can be used for the development of research robot software and for the investigation and estimation of hardware.

The developed physical model is used for educational purposes and practical experiments.

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Aldis Baums, Andris Gordjušins, Georgijs Kanonirs. Autonoma mobila pētnieciska ārpustelpu robota izstrāde
Darbā piedāvāta metodoloģija autonoma mobilā robota izstrādei. Tajā ir četri izstrādes soļi. Pirmajā solī sensoru un aktuatoru klasteru modelis tiek lietots, lai atsevišķās robota aktivitātes fāzēs veiktu robota reālā laika analīzi. Lai veiktu uzdevuma izpildei nepieciešamā laika apjoma analīzi, tika izmantotas divas metodes. Ar pirmo metodi robots ir kā cietā reālā laika sistēma ar secīgi izpildāmām darbībām un uzdotiem darbības nobeiguma termiņiem. Ar otro metodi robots ir kā sistēma, kas darbojas r gan ar striktu, gan vāju nobeiguma laiku. Šī metode saucās par derīgā laika funkciju (time/utility function (TUF)). Otrajā solī atbilstoši reālā laika analīzei tiek izvēlēta un izpētīta sistēmas programmatūras-aparatūras arhitektūra. Trešajā solī tiek izstrādāts un izpētīts robota fiziskais modelis. Ceturtais solis ir veltīts darba prototipa izstrādei.
Metodoloģija tika veiksmīgi pielietota robota fiziskā modeļa izstrādei. Modelis spēj darboties autonomi, izpildot iepriekš ieprogrammētu algoritmu vai, nepieciešamības gadījumā, ar roku vadāmā režīmā. Datu pārraide starp operatoru un robotu notiek caur internetu. Nākošais solis – izstrādāt pilna izmēra mobilā robota prototipu.
Izstrādāto pētnieciskā robota fizisko modeli var izmantot algoritmu izstrādei un atkļūdošanai, aparatūras līdzekļu izstrādei un izmēģinājumiem, studentu apmācībai un eksperimentu veikšanai.

Алдис Баумс, Андрис Гордюшинс, Георгийс Канонирс. Разработка автономного мобильного исследовательского робота
В статье представлена методология разработки автономного мобильного исследовательского робота, включающая в себя 4 шага. На первом шаге, для того, что бы провести анализ необходимого на исполнение задачи реального времени, а также представить структуру робота, используется модель, представленная в виде сети кластеров с сенсорами и актуаторами. Для анализа количества, необходимого для исполнения задачи реального времени, используются два метода. При анализе первым методом робот представлен как система жесткого реального времени, в которой все действия исполняются последовательно и они четко ограничены во времени. Вторым методом робот описан как система, действия которой, имеют жесткие и мягкие крайние сроки исполнения. Данный метод называется функцией времени-полезности (time/utility function (TUF)). На втором шаге происходит выбор и исследование архитектуры программно-аппаратной части мобильного робота в соответствии с результатами, полученными при анализе затрачиваемого реального времени. На третьем шаге происходит разработка и исследование физической модели мобильного робота. На четвертом шаге происходит разработка прототипа робота.
Методология была успешно применена при создании физической модели мобильного робота. Модель способна действовать автономно, исполняя заданную программу, а также в случае необходимости, может быть переведена в ручной режим управления. Передача данных между оператором и роботом в данной ситуации осуществляется через интернет. Следующий шаг в разработке – создание полноразмерного прототипа мобильного робота.
Созданная физическая модель может быть использована при создании и отладке алгоритмов, испытании и разработке аппаратных средств, а также обучении студентов и проведении экспериментов.