TINYPHOON
A Tiny Autonomous Mobile Robot

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***Abstract*— In this paper the system architecture of a tiny autonomous mobile robot, called Tinyphoon, is described. The robot is a two wheeled differentially driven (2WDD) robot, which fits with all its components into a cube with an edge length of only 75mm. An outstanding feature is its high-speed onboard vision system comprising a small digital CMOS camera and a very fast and low power signal processing unit. Tinyphoon can not only be used as a soccer playing robot in the category MiroSOT, but also as a fully autonomous wireless-enabled robot for many different applications.**

I. Introduction

Tinyphoon[1] is a two wheeled differentially driven (2WDD) robot, distinguished by its powerful, compact and modular architecture. It is the further development of Roby-Go [1]. Unlike Roby-Go, Tinyphoon is able to act autonomous without any help of a host computer, as it is usual for soccer playing robots of the category MiroSOT. Robot soccer [2] was introduced in 1994 with the theoretical background to develop multi-robot adaptive, cooperative, autonomous systems solving common tasks, a so-called Multi Agent System (MAS) [3]. A group of robots must interact and self-organize in order to achieve the common given goal. For our project, other technical aspects beside the cooperative and coordinated behavior where the increase of local processing power while miniaturizing the system, a precise movement and an increased power efficiency. In robot soccer there are several leagues leagues differing in the size of the robots, the number of robots in a team and the system configuration.

Generally speaking, regarding the division of labor between the components of a soccer team, namely between the host computer system and the autonomous mobile robots, three system configurations are defined:

- Remote brainless system
  In this configuration, an external workstation is used to process the data obtained from a vision system and to send the resulting commands to the different robots on the field. The robots just contain modules for propulsion, communication and controlling.
- Vision-based system
  This system can be described as the step from the remote brainless to the robot-based system, as some of the intelligence is transferred from the main computer to the single agents, but the control of the vision system and the strategic coordination still remain tasks of the host unit.
- Robot-based system
  This configuration is clearly the goal for all technical research in this field. The robots act completely autonomously, thus processing data from their onboard sensors. Furthermore they communicate with the other cooperating robots and generate own strategies towards their goal.

In robot soccer two different organizations exists, which organize competitions. The FIRA[2] is one of them and organizes competitions in the following categories: NaroSOT, MiroSOT, RoboSOT, KheperaSOT and HuroSOT. The category MiroSOT (Micro Robot Soccer Tournament) (Fig. 1) is basically a vision-based one, however typically it is performed as a remote brainless system. In this configuration two teams play soccer against each other on a black playground with an orange golf ball. One or two host computers per team control the robots. The size of the robots is limited to a cube with an edge length of 75mm. Each robot has to be marked on its top with at least one color. The positions of the moving objects on the playground are detected by the aid of their color information.

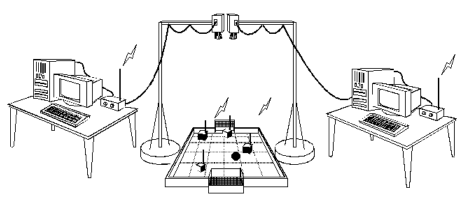

Fig. 1. Overall System

The playground is supervised by a camera mounted above the playground. The image of the camera is processed by a host computer located next to the playground. A vision system detects the position and orientation of the moving objects which is the information basis for decision-making. The result of the program on the host computer is a trajectory, which is transmitted

[1] `http://www.tinyphoon.com`

[2] Information about the FIRA rules can be found at `http://www.fira.net`

via a radio communication to the robots. The robot has to follow this trajectory as accurate as possible [4].

II. Related Work

Tinyphoon is the further development of Roby-Go [5], which was released first in spring 2000 and was developed basically as a pure soccer playing robot. Roby-Go (Fig. 2) is a two wheeled differentially driven mobile robot, which was designed as a remote brainless system robot.

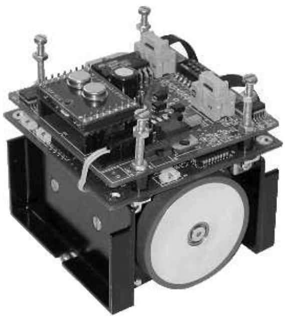

Fig. 2. Roby-Go

According to the FIRA MiroSOT rules Roby-Go fits into a cube with an edge length of 75mm. It has two DC motors with digital encoders, which are controlled by a microcontroller. The task of the microcontroller is to generate PWM (Pulse Width Modulated) signals for the DC-motors according to the measurements of the encoders and the given desired values. The desired values, in the case of Roby-Go, the velocity and the angular velocity, specify the trajectory, which the robot has to follow as accurate as possible. These desired values are transferred via radio from a host computer to the robots. For increasing the robots acceleration and prevent slippering of the wheels the robots is equipped with two two-axis acceleration sensors [6].

Roby-Go was the first European MiroSOT soccer robot and became the prototype of nearly all European MiroSOT robots. It was used or copied by several European robot soccer teams and took many medals at several World or European Championships. Two examples of the further developments are Roby-Speed and Roby-Naro [7].

III. Problem Analyzes

The weakness of remote brainless robot soccer systems is that their robots are not able to act autonomously. However, the goal of each robot's development is a fully autonomous robot, thus a robot-based system, such as envisioned for Tinyphoon. For the system requirements of Tinyphoon it was taken into consideration that the robot can be used further on as a soccer playing robot, but also as a fully autonomous robot. In case of a soccer playing robot, Tinyphoon should be able to act in a vision-based system. In such a system from time to time the robot takes control of the situation and may act independently. For example if the robot is close to the ball, the robot can hit the ball by itself. The robot can do this more precise than a host computer due to the significant dead time of radio transmission between computer and robot. In the case of a fully autonomous robot (robot-based system), the robot has to be able to act without any help of a host computer.

A mobile robot is a combination of various physical (hardware) and computational (software) components. In terms of hardware components, a mobile robot can be considered as a collection of subsystems [8]:

- *Locomotion:* how the robot moves through its environment;
- *Sensing:* how the robot measures properties of itself and its environment;
- *Reasoning:* how the robot maps these measurements into actions; and
- *Communication:* how the robot communicates with the environment

In addition to the above listed subsystems, the following requirements for the overall construction of Tinyphoon are taken into account:

1) For the robot:
    - Functional requirements:
        - Autonomous
        - Robot cooperates in a team
        - Robot operates in an environment with moving obstacles (adversarial robots)
        - Planning based on the symbolic representation as well as on reactive behavior
    - Non-functional requirements:
        - Hardware
            * Size: maximum of 75x75x75mm
            * Two wheeled differentially driven (2WDD) robot
            * Real-time radio communication
            * Low energy consumption electronics (¡1,5W)
            * High computational power (¿ 300MIPS)
        - Reusability of hard and software components for different robot systems
2) For the subsystems:
    - Functional requirements:
        - Configuration and communication "language" for data transmission between the units as well as the robots
        - Memory-oriented data distribution
        - Message-oriented event triggering
    - Non-functional requirements:
        - Hardware
            * Modular design: Smart components linked via a real-time bus system
                · Vision Unit (Mono and/or Stereo Vision System)
                · Motion Unit
                · Ultrasonic Unit
                · Reasoning Unit

– Software:
  * Hierarchical and modular software design
  * Fast real time detection, decision and planning system; granularity of 20ms.

Building up an autonomous robot is a complex task combining several technical disciplines like mechanical engineering, control engineering, electrical engineering, embedded systems design and, of course, computer science. The challenge of the Tinyphoon project was to integrate a high performance modular platform having minimal space and energy requirements and being modular for future expansion via a real-time bus system. The envisioned overall system architecture is shown in Fig. 3.

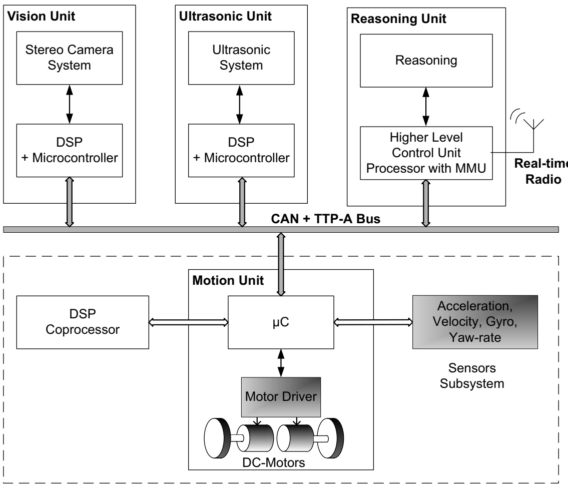

Fig. 3. Structure Of Tinyphoon

A combination of a Time Triggered Protocol [9] (TTP) and CAN bus is proposed to support real-time memory-oriented (TTP) as well as message oriented (CAN) communication protocols and to make use of the advantages of each of the protocols.

In order to be able to extend the system gradually and to improve the design based on the experience made, we decided to build a first robot, still fully autonomous, that consists of a subset of the above shown modules having limited capability regarding the performance of the vision system and processing power available for the reasoning system.

IV. Realization

The overall system was designed based on the requirements listed above. Tinyphoon (Fig. 4) consists of a mechanical part including the power supply and an electronic motherboard, which includes two processor modules and a radio module. The vision system was performed as a mono system which is well suitable for ball recognition or the recognition of other simple objects of known size.

Fig. 4. Tinyphoon

A. Basic System's Architecture

The basic system's architecture of Tinyphoon which has been realized so far is shown in Fig. 5.

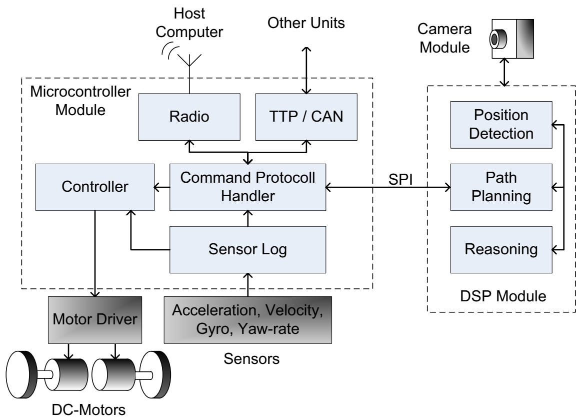

Fig. 5. Basic System's Architecture

The motor drivers and basic sensor systems required for trajectory control as well as position estimation are controlled by a microcontroller module that also provides communication interfaces to other wired units on the robot itself as shown in the overall system architecture (Fig. 3) and a wireless communication interface to other peer robots or a central computer. The DSP module on the right of Fig. 5 is a multipurpose embedded system module with plenty of memory and processing resource to performs path planning and other tasks such as position and object detection. In a later stage these other tasks will run on separate hardware units adding much processing capability to the overall system.

B. Tinyphoon's Mechanics and Hardware

The robot's mechanics is shown in Fig. 6. It consists of two DC-motors, which are connected over a single stage gear to the wheels. The wheels have roller bearings. The robot reaches a speed up to 2.54m/s with an acceleration of 5m/s2. The tolerance of the motion unit is less than 0.5cm/m. Based on the design the robot has a low-lying center of gravity. The robots chassis consists of fiber-reinforced plastics and has a symmetric design. Furthermore the motion unit contains the power supply.

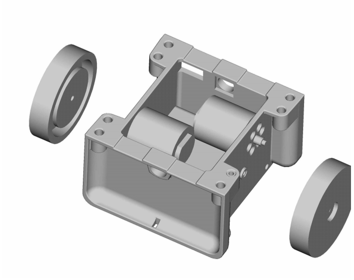

Fig. 6. The Robot's Mechanics

Due to the small overall size of the robot the whole design leads to a complete proprietary development of interconnected deeply embedded system. The electronics (Fig. 7) include two core modules[3]; one core module is based on the XC167 microcontroller from Infineon[4] hosting the motion control. The other core module is based on the Blackfin family of digital signal processors (DSP) from Analog Devices[5] hosting the path planning, the mono vision system and the reasoning part. Both processors are linked via a serial port interface (SPI). For the Blackfin core module a single-core module based on the BF533 as well as a dual-core module based on the BF561 can be used, nearly doubling the performance of the embedded system.

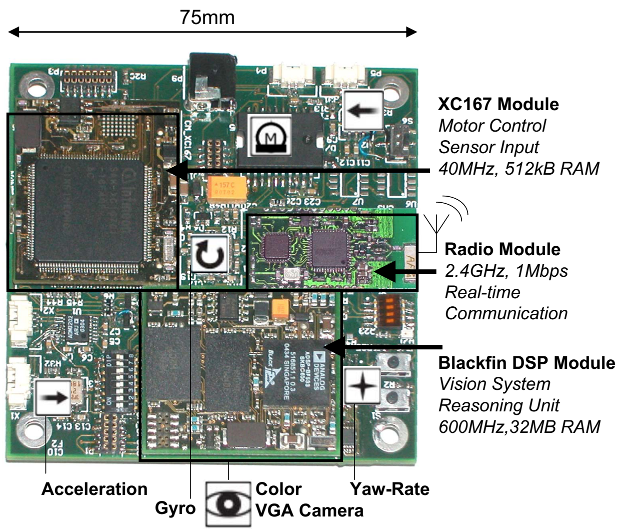

Fig. 7. Tiny Motion Board

For inter robot communication a proprietary radio module is used based on a Chipcon[6] CC2400 chip operating at 2.4GHz and 1Mbps. A proprietary wireless system had to be developed because non of the existing standards like Bluetooth, ZigBee or WLAN did meet the requirements (multi-point and real-time communication, low power consumption, flexibility). Beside the dual channel magnetic encoder with a resolution of 512ppr, which are mounted directly at the DC-motors, the robot is equipped with two acceleration sensors (10g), a gyro sensor (for improved curve keeping) and a yaw rate sensor which is used for absolute angle estimation. It is most accurate ($<$3degree) when the robot is not moving and there are no other robots or magnetic objects a few cm next to it.

C. Tinyphoon's Software

The software architecture of Tinyphoon is modularly designed and consists of the following main units:

- Motion Unit
- Vision Unit
- Reasoning Unit

The software modules are spread over the XC core module and the DSP core module, whereas the DSP functions as a coprocessor and handles the path planning, which needs a lot of computational power depended on the algorithm used. The mono vision system is the only sensor in the system, which provides information about the environment. Besides the vision unit also the reasoning unit is located at the DSP which works fine as long as there are enough MIPS available. Based on the goals of the robot the reasoning unit generates tasks based on the data provided by the vision system. These tasks are executed by special movements of the robot.

The Motion Unit

The task of the motion unit is to control the DC-motors in order to stay on a trajectory as accurate as possible. The trajectory is calculated based on target positions the robot has to reach or pass through. These target positions are generated by the reasoning unit based on the information of the vision system in order to fulfill the robots goals. The trajectory is regenerated every 10ms. For calculating the trajectory a simple pass planning algorithm is used [10]. This kinematic approach generates piecewise circular arcs based on a number of possible different sets of boundary conditions in the target positions. The robots movement is specified by its translatoric velocity v_R and its angular velocity ω_R.

The translatoric velocity and the angular velocity are the desired values for the movement control of the robot. The interval of the translatoric velocity is between -2.54m/s and +2.54m/s. The accuracy of this desired value is 0.01m/s. For the angular velocity applies that the interval is between -25.4rad/s and +25.4rad/s with an accuracy of 0.1rad/s. The mechanical part (Fig. 8) of the mini robot has a behavior of a homonymic cube. To convert the desired to the velocity of the left wheel $v_{R,L}$ and the right wheel $v_{R,R}$, which is used by the controller, the kinematic constraint for the wheels is used.

[3]Detailed information about the used core modules can be found at `http://www.tinyboards.com`

[4]Detailed information about the microcontroller can be found at `http://www.infineon.com`

[5]Detailed information about the BF533 and BF561 can be found at `http://www.anaolog.com`

[6]Detailed information about the radio chip can be found at `http://://www.chipcon.com`

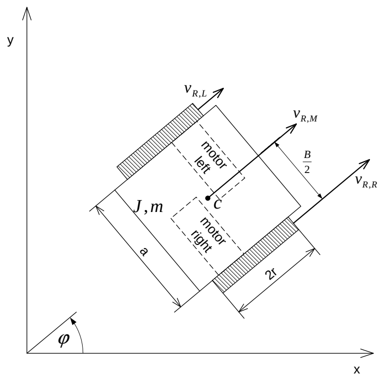

Fig. 8. Mini Robot Model

For controlling the robot two independent recursive digital PID controllers are implemented (Fig. 9), one per each motor and wheel respectively. The desired value, which were given as translatoric and angular velocity is converted to the velocity of the left and the velocity of the right wheel $(v_{R,R}, v_{R,L}) = f(v_R, \omega_R)$.

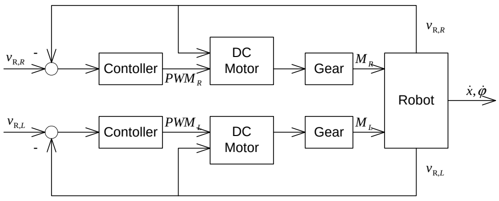

Fig. 9. Control Mechanism of the Robot

The controller of the mobile platform generates a PWM Signal (PMW_1, PMW_2), which is equivalent to a direct current u. The motor converts this signal depending on its actual rotation speed (ω_1, ω_2) into a torque $(\overline{M}_1, \overline{M}_2)$. The torque takes effect over a gear with a gear ratio i on the wheel, which has the radius R. These torques (M_1, M_2), which are effecting on the wheels, result to an acceleration $(\ddot{x}, \ddot{\varphi})$ $(\dot{x} = v_R$ and $\dot{\varphi} = \omega_R)$of the robot. This leads to a wheel's velocity $(v_{R,L}, v_{R,R})$ of the robot.

The Vision Unit

Tinyphoon is equipped with a mono camera system. However, the robot is equipped with two CMOS Camera, one at the front side and the other one at the back side of the robot. By software the robot can switch between the two cameras to obtain a front and rear view of the environment. In robot soccer it is important to switch between front and back because turning the robot would take up too much time. In Fig. 10 the robots's view is shown.

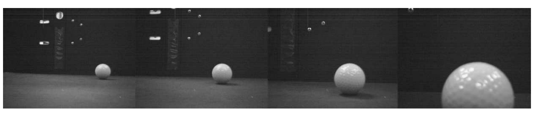

Fig. 10. The Robot's View

The algorithm described in [11] is summarized in the following. In a first step edge detection and color recognition is performed in one pass by a single software loop and two distinct image frames derived from the original frame are stored in memory. Figure 11 and figure 12 show a sample of the two images directly obtained from a main memory dump.

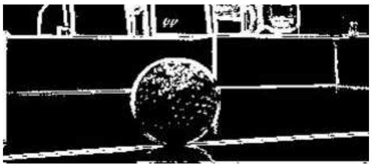

Fig. 11. Edge Image

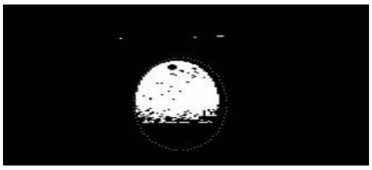

Fig. 12. Color Marked Image

Even though one bit per pixel would be enough for the black and white images, 8 bits are used to mark certain regions for later processing. Most edge detection approaches use local operators (such as the laplace or sobel operators) and require a matrix operation for each pixel and hence multiple loops are required. Instead of using local operators we use a simple and efficient method for edge detection that requires only two comparisons for each pixel. This approach consists of comparing the Euclid distance between each pixel and its upper and left neighbor with a certain threshold. To further minimize the loops of the algorithm we combined the edge detection and color detection process in a single loop. In this loop another operation takes place which we call ”short line detection” or SLD optimized for circular objects. This allows making a pre-selection of relevant edges that might be part of the objects to be found. The short line detection operation marks all relevant pixels that are part of short lines (from 20-50pixels in the case of ball recognition) and stores these lines in a table. With this feature, the search of the objects is reduced to a local search in the region of the short lines. The advantage can especially be seen in objects such as a ball, which has the characteristic of being always a circle from whatever perspective the image was taken. In a second step, smoothing of the color patches is performed to eliminate the fraying edges with an ”opening” followed by a ”closing”, a well known approach in image processing. In the case of a ball the short line table is consulted, the first line extracted and in 45 degree angle a search is started in every direction to find another short line which might be part of the circle. With this approach up to 50 frames per second of QVGA (320 x 240 px) can be processed in real-time.

The Reasoning Unit

A key property of autonomous robots is their ability to make decisions by their own without a master or supervisor. In the current version of Tinyphoon this part is performed very roughly. Simple if-then rules create decisions based on information of the environment provided by the Vision Unit. However the reasoning unit is a main part of our current research. A fuzzy based decision making algorithm [12] designed for the robot's needs is under development. Great importance is attached to the handling of noisy data and the hard real-time constraints of fast acting robots. The Reasoning Unit will be a main part of our further research.

V. Results and Further Research

It was some challenge to develop Tinyphoon from scratch, however this robot has turned out as a very good testing bed for multi agent systems. Due to its modular design all of its parts can be used for other, not only robot applications. Currently Nano [13] a very small sixed legged robot will be equipped with Tinyphoon's vision system.

Meanwhile the robot was presented on the largest exhibition for embedded systems in Europe, at the Embedded World 2004 in Nürnberg and in the USA (Redmond: Microsoft Headquarter and San Francisco: Embedded System fair) as well as at several events in Austria.

In future Tinyphoon will give us the chance to make research on several topics of multi agent systems and to develop advanced algorithms for cooperating autonomous mobile robots. Currently we are going to improve nearly all parts of the robot's software. We are going to develop an energy optimized algorithm for path planning, and an adaptive controller for the controlling of the DC-motors. The parameters of the robot will be adapted by the reference values of the acceleration sensors. This research is supported by the Austrian Science Fund (FWF)[7]. For the vision unit a pivoted stereo camera system is being developed [14], which will run on an own hardware board. For the reasoning unit a fuzzy based decision making algorithm is being developed [12]. The reasoning unit will be performed on a powerfull propietary hardware board. In addition the communication between the boards using TTP/A will be improved.

Acknowledgment

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[7] `http://www.fwf.ac.at`

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