

# A DISTRIBUTED HARDWARE-SOFTWARE ARCHITECTURE FOR CONTROL AN AUTONOMOUS MOBILE ROBOT

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**Abstract:** In this paper, we introduce a hardware-software architecture for controlling the autonomous mobile robot Kapeck. The Kapeck robot is composed of a set of sensors and actuators organized in a CAN bus. Two embedded computers and eight microcontroller-based boards are used in the system. One of the computers hosts the vision system, due to the significant processing needs of this kind of system. The other computer is used to coordinate and access the CAN bus and to accomplish the other activities of the robot. The microcontroller-based boards are used with the sensors and actuators. The robot has this distributed configuration in order to exhibit a good real-time behavior, where the response time and the temporal predictability of the system is important. We adopted the hybrid deliberative-reactive paradigm in the proposed architecture to conciliate the reactive behavior of the sensors-actuators net and the deliberative activities required to accomplish more complex tasks.

## 1 INTRODUCTION

The control architecture of an autonomous mobile robot aims qualify the vehicle for operating in its environment using its computational and physical resources. An instance of control architecture must guarantee the accomplishment of its own tasks in a robust-stable way. There are many proposed architectures, but there is not a definitive paradigm that implementates all the functionalities required (Medeiros, 1998).

The more representative paradigms are the hierarchic, reactive and hybrid (deliberative-reactive) paradigms. In the literature, we can find several examples of classical control architectures: NASREM, Subsumption, AuRa, SFX, Saphira and TCA (Murphy, 2000), PyramidNet (Roisenberg et al., 2004), SHA (Kim et al., 2003), hybrid architecture proposed by Adouane (Adouane and Le Fort-Piat, 2004), CO-HBRA (Heinen, 2002), Ly architecture (Ly et al., 2004) and LAAS architecture (Alami et al., 1993).

A well projected architecture is essential for implementing complex robots. It must have different kinds of hardware and software modules. Moreover, architecture must lead the implementation and the relationship of the modules.

This work firstly specify a hardware-software ar-

chitecture for the Kapeck robot. In a second moment, this architecture will be used to implement a control organization. Finally, an experiment was made to demonstrate the proposed architecture.

## 2 HARDWARE ARCHITECTURE

The Kapeck (Figure 1) is a wheeled non-holonomic multi-task robot. The robot has a differential locomotion system. It has 1 stereo head with 2 cameras and 1 sonar belt with 8 sonars. Moreover, Kapeck has 2 manipulators with 5 degrees of liberty, but in the current stage of the project, the manipulators modules are not included in the proposed architecture, but the modular feature of the architecture makes easy the inclusion of these modules in the future.

The differential locomotion system has 2 independent wheels with 1 DC motor each one. In addition to the motor wheels, there are 2 free wheels, without motors. Each motor wheel has 1 attached optical encoder. These optical encoders, as all encoders used in Kapeck, generate 1024 pulses per revolution.

The stereo head has 5 motors with attached optical encoders. There are 2 CCD cameras. These cameras have 1024X768 per pixel max resolution. They cap-

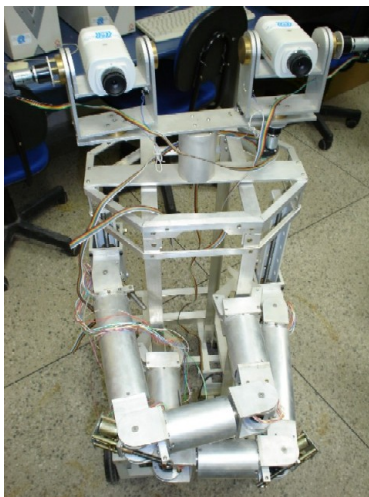


Figure 1: Robot Kapeck.

ture 30 frames per second.

All the sensors and actuators (just not cameras) were attached to a CAN bus (Bosch, 1991). The CAN protocol was developed in the Bosch Laboratories for the automobilist industry, but nowadays this protocol is used in other areas, as robotics. The CAN is very suitable for systems with many sensors and actuators and time constraints. This protocol can perform with multiple masters or in master-slave mode. It supports velocity of 1 Mbit/s in distances up to 30 meters. The maximum distance supported by CAN is 5 kilometers. When used in this mode, the maximum velocity reached in a CAN bus is 10 Kbit/s.

Due to the short sampling periods needed to access the sensors and actuators, the presence of real parallelism in the execution of the robot process is needful. Thus, the proposed hardware architecture of Kapeck (Figure 2) was developed to allow distributed processing, using the robot 10 processors. This architecture is modular, which means the inclusion of new hardware modules, like the software ones, is possible and easy.

The hardware architecture is composed of 1 desktop computer, 2 embedded computers and 8 microcontrolled boards. The embedded computers and microcontrolled boards are inside robot. This hardware configuration permits the real parallel execution of the software modules of robot.

The monitor computer (Figure 2) stays outside Kapeck and communicates with the robot through a wireless net (IEEE 802.11b). This computer has the user interaction software module. This module watches and interacts with Kapeck.

The kapeck1 computer (Figure 2) contains the software responsible for the deliberation of the robot.

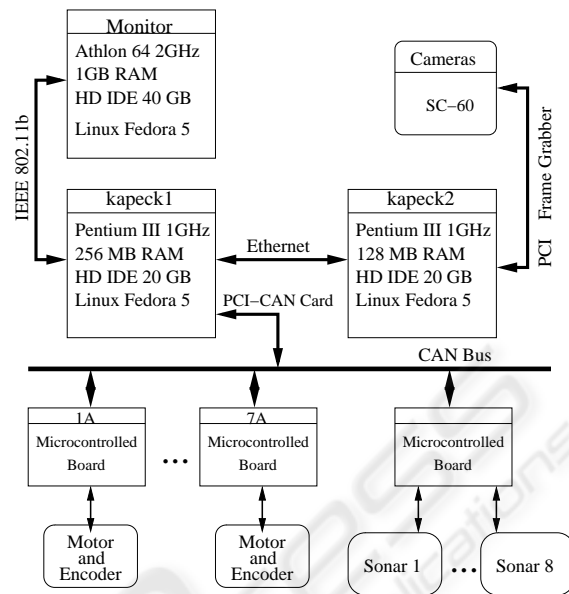


Figure 2: Hardware Architecture.

It is responsible for the interface with the monitor computer, passing to user interaction software module information about the robotic system. Moreover, kapeck1 can execute commands passed by monitor.

The kapeck2 computer (Figure 2) contains the vision system (visonSis). The vision system was placed in a separated computer due to its great computational requirement. This computer communicates with the kapeck1 using a TCP/IP Ethernet peer-to-peer net (crossover cable).

The microcontrolled boards are responsible for the lower control of the sensors and actuators of Kapeck. In this way, there is a performance gain of the robotic system due to the dedicated processing of these boards, releasing the embedded computers to other tasks. These boards are connected to a CAN bus configured in master-slave mode. The CAN bus is connected to the kapeck1 computer. Only the master of the CAN bus, contained inside kapeck1, can permit the access of sensors and actuators to the bus. All the boards have a PIC 18F258. This microprocessor was chosen due to its embedded support to CAN protocol. It also has PWM (Pulse Width Modulation) generator, timers and IO ports, needful to the applications. There are 2 kinds of boards, one called motor controller board, and another called sonar controller board.

The motor controller board is responsible to generate the PWM signal for one motor through the PID (Proportional Integral Derivative) control algorithm, receiving from the high level controller the position references or the velocity references. This board also

has the function of acquiring encoder measurement. When the board is attached to a stereo head motor, the board receives a limit switch signal. The measurements are returned to `kapeck1` computer. The embedded PID control algorithm uses the measurements of encoder and limit switch. The sampling period experimentally chosen to the control cycle of the embedded PID controller is 10 ms.

The sonar controller board is responsible for the sonar functioning. It collects asynchronously sonar measurement when `kapeck1` requires such measurements. The board returns to `kapeck1` the range measurement to the nearest obstacle.

### 3 SOFTWARE ARCHITECTURE

To take advantage of the distributed hardware of Kapeck, the software modules of robot must be able to execute in parallel way. To make it possible, this work proposes two mechanism that permits parallel execution of software modules. One of them is the blackboard. The blackboards are shared memory area that permits the interaction between software modules (Hayes-Roth, 1985). The other mechanism is a logic representation of the CAN bus called `procCAN`.

#### 3.1 Blackboards

The blackboards are implemented by 3 C++ class called `bBoard`, `bBoardAtt`, `bBoardRe` and the software module called `bBoardServer`.

The `bBoard` class is used to create and destroy the blackboards. This class also manages the access to the blackboard created in mutual exclusion, using semaphores. It is used by the system initiator modules, responsible to initiate the other software modules and create all blackboards and semaphores used to exchange information inside the robot. All blackboard, when it is created, receives an unique identification key (ID).

The `bBoardAtt` class is used to attach to existing blackboards. This class provides the read-write primitives of blackboard.

The `bBoardRe` class has the same methods and it functions like the `bBoardAtt`, but it is used to attach to a remote blackboard, created in another Kapeck computer. The utilization of local and remote blackboards is transparent to the client program, because both classes have the same read-write methods.

The `bBoardServer` is a software module implemented in both embedded computers. It uses instances of `bBoardAtt` to accomplish the read-write

operations of local blackboards in the name of the remote clients.

An example of architecture that uses blackboards is the COHBRA architecture (Heinen, 2002). COHBRA has a central blackboard where the software modules share information. This approach is different of the one used in this work, where there are many distributed blackboards.

#### 3.2 `procCAN`

This class makes transparent to the software modules the hardware features of the robot. The existence of this class makes easy hardware alterations of the Kapeck, since it disconnects the software modules implementation from the hardware modules. The software modules operate on the logic CAN bus, that encapsulates the real CAN bus.

The CAN protocol has a native mechanism that controls the simultaneous access to the bus. It uses the CSMA/CA protocol (Carrier Sense - Multiple Access with Collision Avoidance) (Bosch, 1991) to do that. However, Kapeck has a node attached to the CAN bus (`kapeck1` computer) that contains many process competing internally for the access to the CAN bus. In this situation, the existence of a mechanism that guarantee the mutual exclusion access of the bus is needed, since the absence of this kind of mechanism can create message collisions before these messages reach the bus.

The mutual exclusion of the bus is guaranteed by using the CAN bus in master-slave mode and using a bus arbiter. All the methods implemented by the `procCAN` class internally require the access to the real CAN bus to the bus arbiter. If the bus is busy and a software module requires the permission to access the bus, the requiring module will be blocked until the arbiter concedes the access permission. When the access permission is conceded, the requiring module must execute the desired actions and after it must signal to the bus arbiter that the bus is free to be used to other modules.

An example of architecture that uses the CAN protocol is the architecture present in Coronel work (Coronel et al., 2005). In this work is used high-level communication protocol, on the CAN protocol, called SCoCAN (Shared Channel on CAN) to control bus access.

### 4 CONTROL ORGANIZATION

The control organization developed for Kapeck (Figure 3) was based in hybrid deliberative-reactive

paradigm. We adopted this paradigm to conciliate the reactive behavior of the sensors-actuators net and the deliberative activities required to accomplish more complex tasks. Thus, the control organization is composed of the following software modules: Perception, Localizer, Cartographer, actionPl, pathPl, refRoGen, avoiderObs, posCon, headCon, refHeGen and visionSis.

The Perception module is responsible for acquires all the sensor measurements. It requires measurements of sonars and encoders, in a fixed sampling period. This module writes in blackboards the received measurements. Perception writes in 3 different blackboards: one to write angular displacement of wheels, other to write angular displacement of head parts and a third blackboard to write the sonars measurements.

The Localizer module was designed to localize the robot in the current map. It reads data from blackboards where Perception writes. This module calculates the robot position using odometry. The calculated robot position is exported to a different blackboard.

The Cartographer maps the environment using data exported by Perception. The map can be constructed in real-time or, in known environment, be a priori defined. The generated or a priori known map is exported to a blackboard. In the experiment presented in this work, we used a priori known topologic map with metric information, implemented as a graph.

The actionPl reads data from blackboards where Localizer and Cartographer export data. Knowing the global task of the robot, this module determines the action to execute. In the experiment presented in this work, the robot global task is to explore a building with many environments until find a known mark. In this way, there are 4 possible actions:

1. Go to the center of a non-explored environment;
2. Explore a non-explored environment using the stereo head;
3. Go to the mark, if and when it is discovered;
4. Go to another non-explored environment.

The topologic map of building is a priori known. The exploration is done using depth search in the graph that represents the connection topology of the building.

In the case of action 1, an action corresponds to go to the center of environment where the robot is. An action 2 corresponds to execute specific movements with the stereo head. These movements are executed when robot reaches the center of the environment. Such actions have as objective to provide to

visionSis a better pose to capture and process the images.

The action 3 corresponds to go to the mark position, discovered by visionSis. This action is triggered only when the robot accomplishes its global task. When this action happens, the building exploration is finalized.

In the case of action 4, an action means go to a non-explored environment. The path from the current environment to the nearest non-explored environment is determined by Dijkstra algorithm (Cormen et al., 2002). All the possible paths are pre-calculated at the initialization of the robot, because the map is a priori known and it has little dimensions (in the case of the experiment of this work). Thus, the actionPl is responsible for the execution of the depth search on the map and for the election of the correct action in each moment of robot execution.

The actions are synchronously passed to the pathPl module. If the actionPl triggers an action 1, the pathPl exports the center position of current environment. If the actionPl triggers an action 2, the pathPl exports the positions that the stereo head parts must reach. If the actionPl triggers an action 3, the pathPl exports the position of discovered mark. If the actionPl triggers an action 4, the pathPl generates a geometric path from the current environment to the final desired one, passing through the environments between them. Two blackboards are used by the pathPl module: One to export the data needed to move the robot from an environment to another; other blackboard to export data needed to move the stereo head parts.

The refHoGen module reads the blackboard where pathPl writes. It generates the reference positions in each sampling period and exports these references in a different blackboard.

The posCon is a reactive module that generates velocities percentages for wheel motors using PID algorithm to move the robot to a position read from the blackboard where refHoGen exports data. These percentages are sent to motor controller board, providing the reference to the embedded controller of them. This module also reads the data exported by Localizer, needed by the PID controller.

The avoiderObs reads sonar measurement acquired by Perception module. The avoiderObs monitors read data in order to identify obstacles in the robot path. If an obstacle is detected, a safety position is generated and exported to the blackboard where refHoGen exports.

The headCon functions like posCon module, but it reads references from blackboard where refHeGen module writes data.

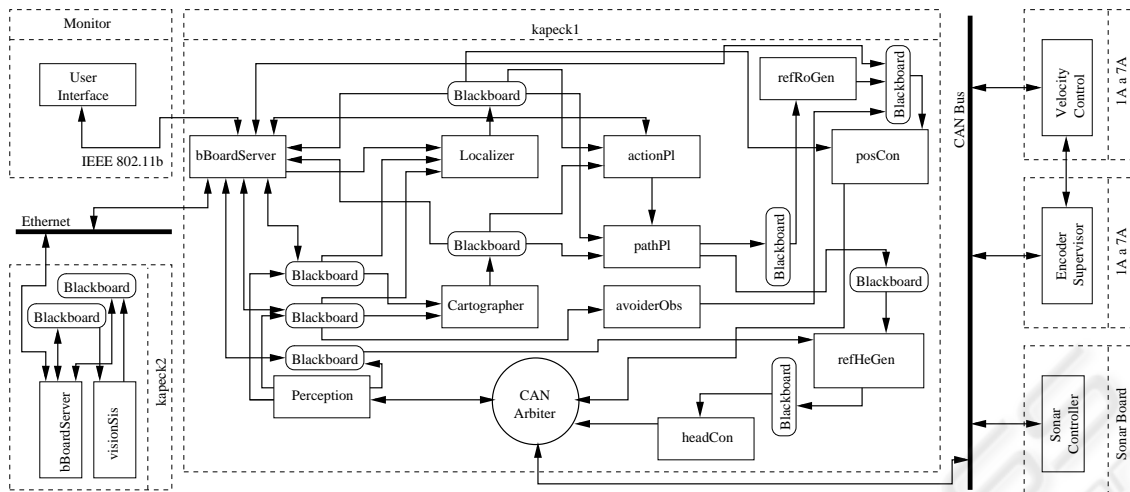


Figure 3: Control Organization.

The `refHeGen` function in to possible behaviors: Standard behavior and Exploring behavior. In the standard behavior, this module generates and exports to a blackboard specific positions possible to reach by the stereo head parts. In the exploring behavior (started when `actionPl` triggers an action 2 and finished when the action 2 finishes), `refHeGen` starts to read and export the positions generated by `pathPl`.

The `visionSis` processes the camera images to find the desired mark. When the mark is discovered, `visionSis` signals to `actionPl`. After this, `actionPl` triggers an action 3. Together with the signal, `visionSis` exports the robot position to a blackboard.

## 5 EXPERIMENTAL RESULTS

The experiment developed in this work to demonstrate the proposed architecture consists in a robot that explores a priori known map to find a mark. When the robot finds the mark, it goes to its position. This experiment contains the following software modules of proposed control organization: Perception, Localizer, Cartographer, `actionPl`, `pathPl`, `refRoGen`, `posCon`, `headCon`, `refHeGen` e `visionSis`.

In the Figure 4 we present the experimental results. In the moments T0, T3, T6 and T10 the `actionPl` triggers an action 1. In the moments T1, T4, T7 and T11 the `actionPl` triggers an action 2. In the moments T2, T5, T8 and T12 the `actionPl` triggers an action 4. In the moment T13 `visionSis` identifies the mark, signaling to `actionPl`. So, `actionPl` triggers a action 3. At this moment, the robot dis-

cards the rest of path generated in moment T12 and goes to the mark, using the coordinates provided by `visionSis`. In the moment T14 the robot reaches the mark and accomplishes the global task.

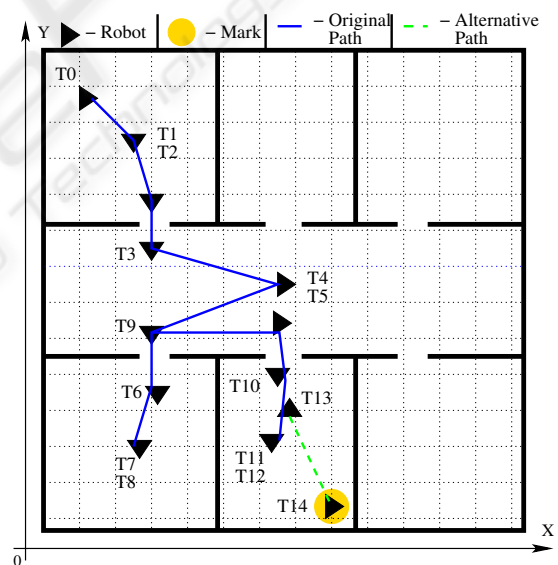


Figure 4: Experimental Results.

## 6 CONCLUSIONS

This work presented the main ideas of a hardware-software architecture for an autonomous mobile robot. In particular, we propose the using of blackboards to implement the interaction between software modules. We also presented the CAN bus access mode, using a logical representation of the real CAN

bus. The proposed architecture tries to manage not only the organization software aspects, but also the hardware organization and the interaction between hardware and software modules. The concepts presented were applied to Kapeck. We pretend in next works improve the software modules of the control organization and develop hardware and software modules to control the manipulators. In the current stage of the work, we use a simple mechanism to coordinate the access to the CAN bus. An evolution of the work could be the utilization of a high-level protocol on CAN.

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