TU Wien, Institut für Flexible Automation

CALINCA
A Compact Autonomous Linkable Intelligent CARRIER

Wolfgang Stubenvoll

Abstract: CALINCA-vehicles are autonomous wheeled mobile transport platforms for indoor environments intended to execute not only logistic tasks but also manufacturing processes on the transport platform itself. The special feature of the CALINCA-vehicles are the small physical dimensions and the mechanical linkability to form rigid structures of multiple vehicles for scalability of transport units according to payload weight or payload area. With this concept a flexible cooperative transport solution for manufacturing purposes is provided e.g. as an alternative for belt-driven pallets.

INTRODUCTION

Future scenarios of cooperative manufacturing suggest multiple modular autonomous transport vehicles and autonomous mobile robots (AMR´s) coupling together and assembling the parts during transport. Rendezvous and docking of transport vehicles and AMR´s is therefore as important as coordinated movement of compliant or rigid linked vehicles to reach the goal of cooperative manufacturing (Levi, 1994).

In case of autonomous mobile robots (AMR´s) cooperation will enhance their capabilities but it is necessary to add some features and/or to change their behaviour. A communication between AMR´s is crucial for coordination of movements.

Research strongly depends on the degree of cooperation which reaches generally from very losely simple geometrical cooperation to the rigid coupling of AMR´s. (Ozake et al, 1993) describes the ACTRESS system where a radio communication system is used to synchronize the motion between the AMR´s without any link. The COMROS-Project at Stuttgart (Levi, 1994) consists of 3 cooperating AMR´s Athos, Porthos and Aramis which are based on the same Roboter-platform. Driving as a convoi and a rendezvous-maneuver with a standing AMR using communication was the research aim of this project.

Several research projects apply rotatory or translatory joints between the AMR´s and measure the relative displacement for controlling the positions relative to the other AMR´s. The METROS-system (Hashimoto and Oba 1993) consists of AMR´s with a prismatic link including a rotary joint to hold the transporting object. The Gunryu robots (Hirose, Shirasu and Fukushima, 1996) have a handling arm which is utilized to attach to another Gunryu robot on the grip stud.

A compliant linkage between two trucks is realized in the OmniMate mobile robot (Borenstein and Evans, 1997). The linkage has two rotatory and one translatory axis equipped with sensors to measure the relative displacements between the two trucks. Each truck has it´s own power supply, motors and odometry sensors. This is used to correct odometry errors of one truck by using the other truck as a reference.

The AMR´s Fred and Ginger at Salford (Eustace, 1993) are coupled with a 6 degree of freedom compliant linkage. Each of the two has 2 translatory and a rotatory linkage of the rigid traverse between them.

Docking of vehicles was already subject of research to position an AMR relative to a fixed target accurately (e.g. docking terminal for loading/unloading, another still standing AMR). Vandorpe, (1995) describes a docking procedure for their AMR LiAS to a docking station and reaches an accuracy of 1cm side distance and 0,5° in orientation with triaural sonar and visual ranging.

The development of a compact autonomous linkable intelligent carrier (CALINCA) led to an autonomous transport vehicle that fulfills the mechanical and electronical preconditions to dock with a rigid linkage to other CALINCA-vehicles and to move coordinated and synchronized multiple linked CALINCA´s. This paper describes achieved results in developing the CALINCA hardware-platform. This will be the basis for further research on rendezvous and docking as well as communication, realtime task distribution and execution to reach coordinated movement.

After presenting the concept of CALINCA the mechanics, electronics and navigation subsystems of a single vehicle focussing on the topics necessary for docking and linkage are described.

1. CONCEPT

The main concept of CALINCA is the linking of multiple small vehicles to a larger cluster of rigid coupled vehicles to increase the payload weight and payload area. It is therefore necessary to have a flat top mounting and payload area. Linking of many small vehicles forms a large flat payload area. The four sides of a single CALINCA-vehicle has to fit to a side of another CALINCA-vehicle with a docking mechanism ensuring not only a withdrawable rigid mechanical coupling but also a number of electrical connections for power supply and communication purposes.

Moving of clusters of vehicles with a rigid coupling need coordination and synchronization of the steering and driving motions of the single autonomous vehicles coupled together which is done with communication between the processors of the vehicles. This is done with high speed communication linkports of the onboard SHARC DSP capable of 40Mbaud each. Linking of CALINCA-vehicles forms also a twodimensional multiprocessor-array of DSP´s (***fig.1***) and enables parallel processing especially to coordinate navigation, sonar and motion.

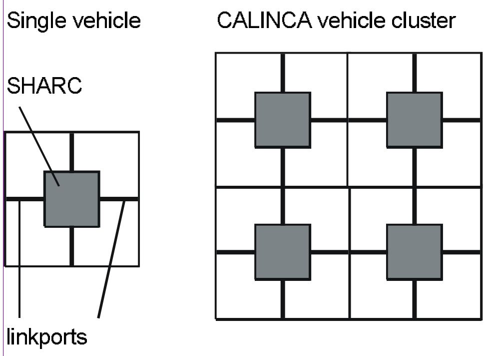


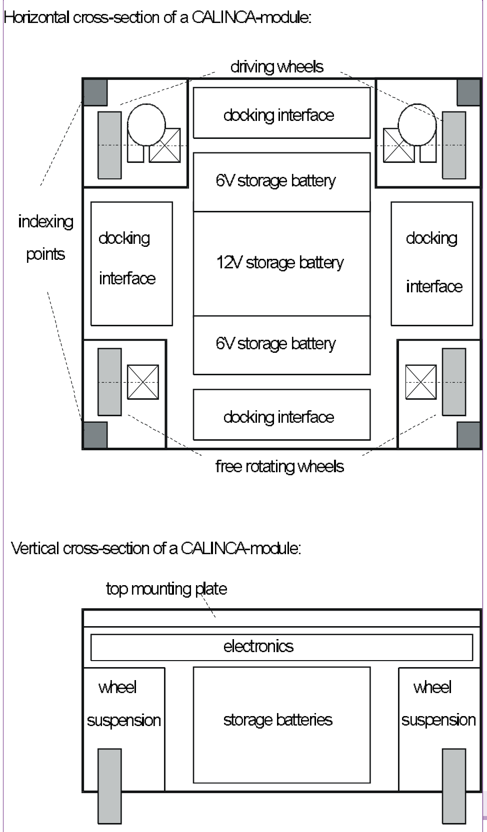
Fig. 1: twodimensional multiprocessor-array built with highspeed communication linkports by docking of multiple CALINCA-vehicles

Especially when moving along a bent path requires that each of the wheels of the vehicles of the cluster has its own correct steering angle dependent on the centerpoint and the radius of the curve.

To reduce the forces applied to the mechanical docking mechanisms the CALINCA-vehicle has four wheels with a spring suspension. This guarantees that every wheel has contact to the ground an can transfer forces (gravitational forces of the vehicle itself or of the payload).

The development of the CALINCA-vehicle has led to the following characteristics:

- payload 10 kg
- minimal payload area 320mm x 320mm
- net weight 16 kg (8kg storage batteries)
- height 160mm, ground clearence 10mm (with maximum payload)
- maximum velocity (flat ground) 0,5m/s
- maximum climbing gradient 10%
- battery powered with 12h operation time
- 4 independently steered wheels with spring suspension and encoders
- 2 wheels with independently controllable driving motors
- indexing capability through 4 inside cones
- 4 docking mechanisms on each side
- ultrasonic sensors for orientation and collision avoidance
- navigation with odometry, ultrasonic sensors and stored maps


Horizontal cross-section of a CALINCA-module:

Vertical cross-section of a CALINCA-module:

***Fig. 2**: Cross-sections of a CALINCA-vehicle*

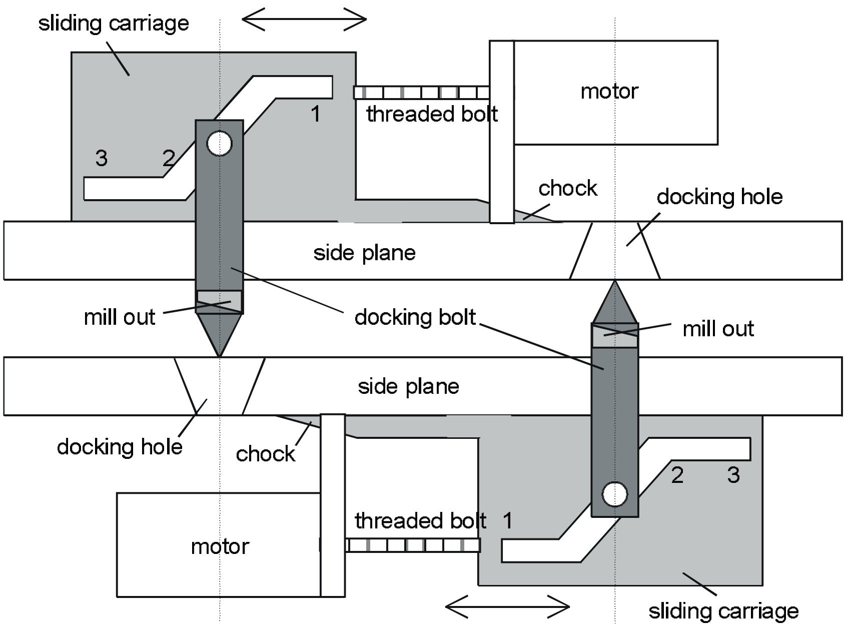


***Fig. 3**: Mechanical docking mechanism*

2. MECHANICS

The chassis of the CALINCA-vehicles consists of a top mounting plate, 4 side traverses, 4 wheel suspension units, the driving gear boxes and the battery holding construction (see ***fig. 2***).

Each wheel suspension unit provides a compliant spring suspension for the wheel and includes the gear box for the steering worm gear, the indexing inside cone and the fixing of the steering position sensors the side traverses and the top mounting plate. The steering gear box is mounted on the chassis the steering forces are transmitted with a telescopic chock-shaft to the up and down moving wheel bearings or the driving gear boxes.

The side traverses connect two wheel suspension units on the ends and also holds the docking interface. It is therefore very easy to enlarge the size of the vehicle by only increase the length of the side traverses. The shape and the size of the wheel suspension units and the wheel bearings or the driving gear boxes remains the same. In case of increased net weight or payload capacity of the vehicle the wheel suspension units have to be reconstructed for application of stronger motors.

The top mounting plate can be easy dismounted from the vehicle by only 4 screws. Application specific mechanisms, part holding structures but also active elements like robot arms can be mounted on the top of a CALINCA-vehicle.

The electronics is situated between the batteries and the top mounting plate and is easy accessible when the top mounting plate is removed.

2.1 Mechanical docking interface

A rigid connection between two CALINCA-vehicles is established with the mechanical docking interface. A mechanism was developed using a single motor only for moving a cone shaped docking bolt into/out of the mechanism and to chock the docking bolt from the other mechanism. The docking mechanism is self-centering to allow a relative positional accuracy of 5mm during the approach and docking maneuvers.

Figure 3 shows the docking mechanism. The motor moves the sliding carriage with a threaded bolt. This causes the docking bolt to move out or into the docking mechanism. In state 1 the docking bolt is completely inside the mechanism. Moving from state 1 to state 2 the docking bolt moves out and reaches the maximum outside extension but the chock is not covering the docking hole. When the docking mechanism is in state 2 it is possible to couple two CALINCA-vehicles. They have to take a position aligning their docking mechanisms and must in the next step insert the docking bolt in the docking hole of the other mechanism.

The mechanism is self-centering because the docking-bolt has a cone-top and the docking-hole has an inside-cone. This is necessary because of the horizontal and vertical position uncertainity of the vehicles. After insertion of the docking-bolts both mechanisms have to transit from state 2 to state 3

which moves the chock in the mill outs of the docking bolts. The CALINCA-vehicles are then chocked and forces can be applied to them. During releasing the sliding carriage is moved from state 3 to state 1 simply freeing the chock and retracting the docking bolt.

3. ELECTRONICS

The electronics of a CALINCA-vehicle incorporates a dual processor system to perform the necessary tasks. A floating point DSP is used mainly for numeric and planning tasks and a microcontroller drives the actuators and reads and converts the sensor-values. The processors are decoupled with a dual-port-RAM. Therefore both processors have unlimited acces to their address- and data-busses and are synchronized via interrupts (see also ***figure 4***).

All the electronics is integrated to a single cross-shaped 4-layer printed-circuit-board with parts placed in surface mount technology on both sides.

3.1 SHARC digital signal processor

The ADSP-21060 SHARC from Analog Devices is used for numeric and planning tasks of the CALINCA-vehicle. The SHARC DSP-core can calculate with 32 to 40bit floating point numbers and its internal IO-processor handles the two serial I/O channels, the 6 linkports with 40 Mbaud each and the transfers over the 32bit address- and the 48 bit data-busses (see also Analog Devices 1995 for more details). These features make the SHARC best suited for the CALINCA-vehicle because the linkports are used for high-speed vehicle to vehicle communication.

The SHARC generates the waveforms of the sonar transmitters and reads the echo-data of the three receivers on each side. The calculation of the echo-locations, the comparison with the map-information, the collision detection and avoidance is done by the SHARC.

A Flash-ROM of 1Mx48bit holds the algorithms, programs and data for the SHARC and the environment information in form of maps. It is easy to replace them in case of program updates and changes of the map information.

In the future it is planned to integrate an IrDA compatible infrared communication on each side for vehicle-to-vehicle communication on-the-fly, for remote control of peripherals (like elevators) and for communication with a notebook PC to establish a man-machine-interface. A quadruple UART will be used to realize the IrDA communication.

Beside the processing of the sonar data the SHARC plans the path of the CALINCA-vehicle from the building-level down to the room-level and calculates the command values for the steering and driving motors. They are stored in the dual-port-RAM and are retrieved by the 80C167 which writes back the actual values of the motor-positions and the other sensors. With the actual sensor-values the odometry calculations are executed.

3.2 Microcontroller 80C167

The main task of the Siemens 16bit microcontroller C167 is to read and convert the sensor values, perform the control-algorithms of the 4 steering and 2 driving motors with an overall cycle time of 2ms. The control algorithms , programs and data are stored in the C167-internal Flash-ROM.

The encoder signals are interpolated to reach a 4 times higher resolution and are fed to the timer-inputs of the C167. The motors are controlled via pulse-width-modulation outputs with the PWM- or capture-compare-units of the C167.

The C167 uses an external 12bit ADC for conversion of the four steering and four suspension sensors (potentiometers) to have a better resolution than its internal ADC. The internal ADC is used for monitoring the power supply lines, motor supply currents, temperatur and humidity sensors. An external real-time-clock (RTC) is used to store important data and to generate wake-up interrupts for the C167.

Precipice sensors are built with infrared reflective sensors and a precipice is detected when the light from the IR-LED is not reflected by the floor and can thus not be detected by the IR-fototransistor. In this case an emergency stop is invoked.

Bumpers are also added to the CALINCA-vehicle but they do not switch-off the driving motors directly by hardware (as required by law) but via software of the C167. This is necessary during the dokking at the front and rear sides because in the docking procedure the bumper-signals must be overridden.

3.3 Electrical docking interface

The electrical docking interface consists of a zero-force connector with 22 pins. With spring contact probes 11 pins are realized and the other 11pins are simple pads. The connector contacts the ground, the 12V and 6V charge lines as well as the 6 lines to establish a linkport connection between SHARC´s of different vehicles.

A proximity sensor is added to control the last millimeters of the approach and dokking maneuvers.

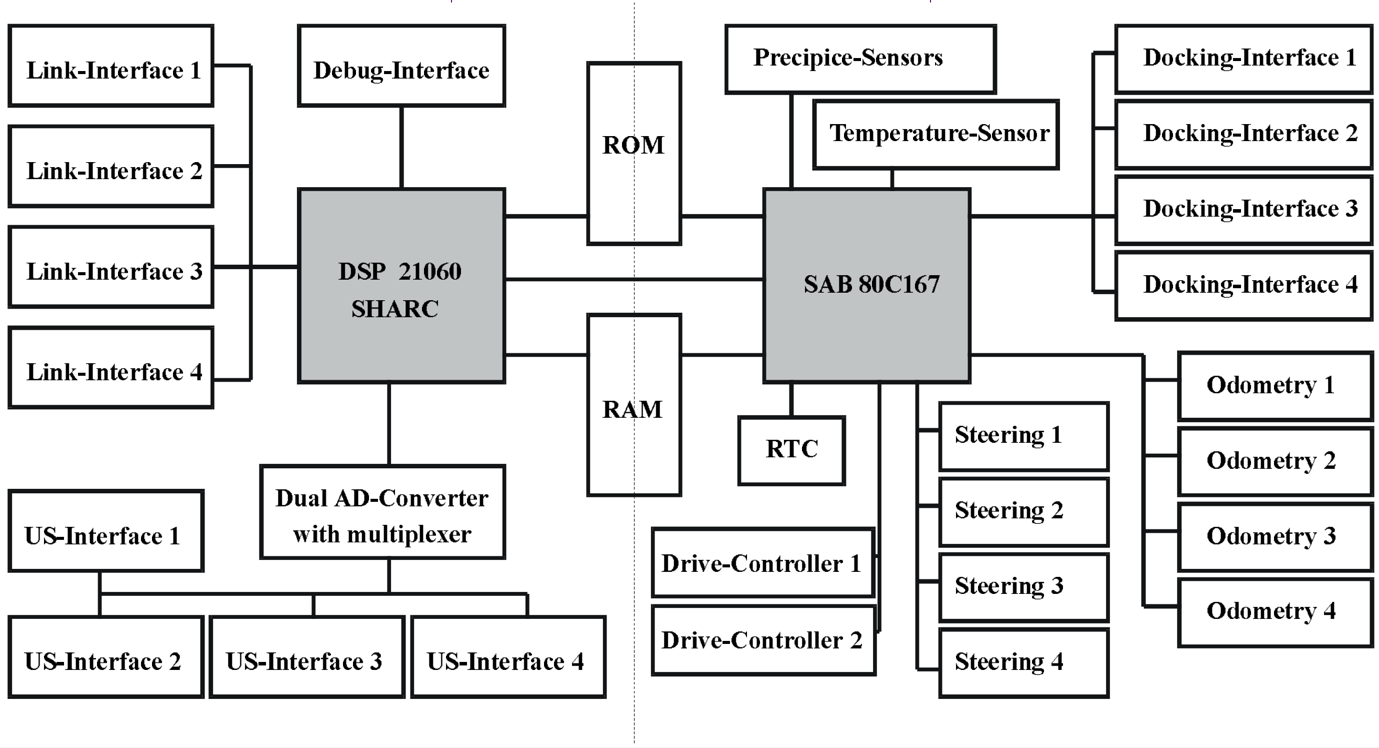


***Fig. 4**. Schematic overview over the CALINCA-vehicle electronics*

3.4 Electrical power supply

The CALINCA-vehicle has two storage battery-subsystems. One with 12V to supply the driving, docking and steering motors and the 6V batteries for energizing the electronics. The capacity of the batteries are chosen in order to guarantee a longer supply for the electronics than for the motors to get a fail-safe behaviour of the vehicle. In case of a low motor energy the electronic is still active and can communicate with other vehicles to call for help. It is possible for a vehicle to tow another vehicle with low electrical power supply. This is done by docking the two vehicles together and the vehicle with much energy transfers its energy via the electrical docking connector to the vehicle with low energy.

The current consumption is measured in every control cycle and thus the amount of the remaining energy can be calculated. If the remaining energy in the batteries is low the SHARC is informed that a recharge is necessary. During recharge the CALINCA-vehicle docks to a recharge-terminal where the docking connector contacts to the 12V and 6V charge line and the C167 controls the charging process of the batteries. To maximize the charging current the SHARC, the C167 and all their peripherals are put in the idle state. The RTC awakes the C167 in certain intervals to control the recharge process. The charge lines are fed through the vehicle so that each vehicle connected to a charging terminal can serve as charging terminal with its docking interfaces.

4. NAVIGATION

A CALINCA-module navigates with internal sensors (odometry) and sensors measuring the environment (sonar). Localization is done with odometry in conjunction with sonar signals which are compared to stored information about the environment (maps).

4.1 Odometry

Encoders mounted directly on each of the four wheel-axes measure the revolution-angles of the wheels. The encoders on the free running wheels are used for more accurate odometry purposes due to minimal slippage compared to the encoders on the driving wheels. The signals of the encoders mounted to the driving wheels are only used to control the motors.

The steering angles and the spring suspension movements are measured with potentiometers which signals are fed to the external ADC of the C167. The vertical movement of the wheel spring suspension is used to correct uneven movements of each wheel separately (and to determine the payload weight). A detailed description is found in Stubenvoll (1998b).

The absolute sensors for the steering position and the spring suspension must be calibrated and the zero position must be stored permanently to get a correct position information for the controller of the steering angles. Calibration must be done in certain time intervals and after excessive mechanical forces have been applied to the wheel suspension.

4.2 Sonar sensors

For our research concerning mobile transport vehicles we use a sensor, based on the time-of-flight (TOF) of the ultrasonic signal. Additionally by analyzing the time difference between the received signals on each receiver 3-dimensional localization of the reflecting objects can be achieved. One transmitter with three receivers - where the transmitter also operates as receiver - is sufficient for realization (similar to Rencken 1995). The horizontal distance between the receivers is as large as possible to get a higher resolution of the horizontal localization of the echo.

The sender emits an ultrasonic signal which propagates like a spherical wave. This wave is scattered back by various objects in the enviroment and is received by the three receivers with a time delay to the sending signal and relative to each other. These time delays of the receiver signals are the basis to calculate the distance, horizontal and vertical angle of the reflector relative to the transmitter/receiver plane.

To avoid mutual disturbance of vehicles operating in the same room or very close together the ultrasonic sending signal of each vehicle is frequency modulated differently from each other. The receiver and the DSP of the vehicle can then easy detect if the receiving signals have the own modulation or was transmitted from another vehicle (see also Stubenvoll and Dimitrova 1998a).

4.3 Stored environmental information

It is necessary to provide maps of the environment for localization and orientation of the CALINCA-vehicles. Maps available in an AutoCAD format can be edited to classify the buildings, rooms and objects in the rooms in terms of their function and of their sonar appearence. A number of predefined objects are available which have to parameterized to represent the real objects. Such predefined Objects are walls, doors, desks, stairs, elevators, etc. where it is assumed that they move very rarely. Objects like chairs, trash-cans, small boxes, etc. are moved very often and do not appear in the environmental information. A collision with these easy movable objects must be done online during movement of the CALINCA-vehicle.

The parameterized objects and the geometrical information of the AutoCAD map of the building or room are converted by a postprocessor to a CALINCA-readable format. These converted maps can be downloaded to the CALINCA-vehicles by docking via linkports or via future IrDA-communication channels and are stored in the Flash-ROM.

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