PROCEEDINGS

53. IWK

Internationales Wissenschaftliches Kolloquium
International Scientific Colloquium

Faculty of
Mechanical Engineering

PROSPECTS IN MECHANICAL ENGINEERING

8 - 12 September 2008

www.tu-ilmenau.de

TECHNISCHE UNIVERSITÄT
ILMENAU

Published by
Impressum

Publisher Herausgeber	Der Rektor der Technischen Universität Ilmenau Univ.-Prof. Dr. rer. nat. habil. Dr. h. c. Prof. h. c. Peter Scharff
Editor Redaktion	Referat Marketing und Studentische Angelegenheiten Andrea Schneider
	Fakultät für Maschinenbau Univ.-Prof. Dr.-Ing. habil. Peter Kurz, Univ.-Prof. Dr.-Ing. habil. Rainer Grünwald, Univ.-Prof. Dr.-Ing. habil. Prof. h. c. Dr. h. c. mult. Gerd Jäger, Dr.-Ing Beate Schlütter, Dipl.-Ing. Silke Stauche
Editorial Deadline Redaktionsschluss	17. August 2008
Publishing House Verlag	Verlag ISLE, Betriebsstätte des ISLE e.V. Werner-von-Siemens-Str. 16, 98693 Ilmenau

CD-ROM-Version:

Implementation Realisierung	Technische Universität Ilmenau Christian Weigel, Helge Drumm
Production Herstellung	CDA Datenträger Albrechts GmbH, 98529 Suhl/Albrechts

ISBN: 978-3-938843-40-6 (CD-ROM-Version)

Online-Version:

Implementation Realisierung	Universitätsbibliothek Ilmenau ilmedia Postfach 10 05 65 98684 Ilmenau

Home / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=17534

53rd Internationales Wissenschaftliches Kolloquium
Technische Universität Ilmenau
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Design, Assembly and Calibration of a Specialized Welding Robot for Repairing Hydraulic Turbine Blades

INTELLIGENT MECHANICS IN ROBOTICS

The article presents the steps of a R&D project aiming at designing and constructing a specialized welding robotic system for recovering material damage on hydraulic turbine blades. The current project proposes a methodology and presents the construction steps of a robotic prototype to automate the welding process with the purpose of repairing hydraulic turbine blades eroded by cavitation pitting and/or cracked by cyclic loading, reducing human risks and increasing the efficiency of the process.

Hydraulic turbines installed in hydroelectric plants are subject to several types of mechanical wearing. The sources of mechanical straining can range from operational conditions of the hydro generator, poor design characteristics, properties of the blade material employed and operation points out of specification as a consequence of overloading [1, 2].

THE PROBLEM CHARACTERIZATION

The most common cause of rotor wearing is the erosion by cavitation pitting [3, 4]. This is a highly undesirable phenomenon in the operation of a turbine. The water that flows through the turbine ducts during operation generates pressure fields on the blade surface that can be below the water vapor pressure in the operation temperature. This extreme operation condition generates vapor bubbles that can be collapsed when they reach regions of abrupt changes in pressure and flow conditions. When such bubbles collapse, they produce high shock pressures, which cause tearing out of bits of metal when the collapse occurs in adjacent regions of the runner blades. This cyclical loading of high amplitude produces fatigue erosion on the blade surface, causing substantial loss of material [5]. Fatigue cracks are more rarely found, but the phenomenon can happen in hardened steels, such as martensitic stainless steels.

An established process for repairing the surface of turbine blades eroded by cavitation or damaged by fatigue cracks is to recover the material flaws by using electric arc welding. The welding process is carried out manually after visual inspection of the blade surface, requiring a halt of the turbine. This is a very harsh human labor condition, in air temperatures around 40℃ and 99% of air humidity for tenths of hours.

Fig. 1- Hydraulic turbine blades damaged by cavitation and crack repairing.

Current Technologies of Arc Welding Processes for Repairing Turbine Blades are briefly listed below, with drawbacks and/or advantages. [6]

Any arc welding process carried out manually

- Quality depends on operator skills;
- Generally positional welding (out of flat position), which implies in the need of deposition rates, consequently, long welding periods;
- Depending on the runner base material, pre-heating is needed, which implies in submitting the welder to a very harsh environment for a long time;
- Poor accessibility of some parts of the blades makes it difficult for a welder to accomplish the repairing process;
- Grinding needed after welding to recover blade fluid-dynamic profile;
- Often layered welding is needed, depending on the depth of the damage;
- Introduction of residual stresses in the resulting runner structure.

Manual Metal Arc Welding – MMA (Shielded Metal Arc Welding – SMAW)

- Low productivity;
- Need for slag removal after carrying out each weld bead during layered welding;

- Quality is highly dependent on welder skills;
- High spatter levels which implies in loss of material;
- Welding equipment is simple.

Manual Conventional Gas Metal Arc Welding – GMAW

- Good deposition rates;
- Arc instability may be of concern;
- Spatter may be a concern, depending on shielding gas;
- Instability in flux of shielding gas due to spatter build up in gas nozzle, which leads to porosity;
- Welding equipment more complex than in the MMA process.

Manual Flux Cored Arc Welding – FCAW

- Very good deposition rates;
- Possibility of including alloying elements in weld material;
- Need for slag removal after each weld bead, which may lead to the presence of inclusions.

Manual Tungsten Arc Welding – TIG

- Very good weld quality;
- Need for highly skilled welder;
- Low deposition rates.

PROJECT GOALS

This project is intended to improve the quality of cavitation damage repairs in hydraulic turbine blades using robotic welding, reducing welding defect rates, material consumption, time-to-repair and overall repairing costs. Besides, the technology proposed can remove weld personnel from harsh environment, achieve a better blade profile and improve weld consistency.

ROBOT DESIGN

For a robot to realize all tasks needed in the application proposed it has to be able to fulfill the requirements below:

- Capacity to operate in any position: horizontal, vertical or inverted;
- Low weight: portability and fixation to the blades;
- Rigidity to deflection: load on wrist occurs in any direction and arm extension;
- High motion accuracy: capacity to reach accurately welding regions from the mapped geometry;
- Availability of parts in the market;
- Control with component interfacing capability;
- Topology making feasible to measure large areas with laser scanning and 3d geometry mapping;
- Large workspace;
- Easiness to be fixed to the turbine blades.

The robotic system proposed has a spherical topology with 5 degrees of freedom, electric stepper motors, rotary and linear actuators and a 2m-diameter workspace. The system has an embedded measurement system with a vision sensor especially built to produce range images by scanning laser beams on the blade surface. The range images are used to construct 3-D models of the blade surface and the location of the damaged spots are recorded into the robot controller in 3-D coordinates, thus enabling the robot to repair the flaws automatically by welding in layers. The robot controller and measurement system are built in FPGA-based reconfigurable microprocessors. The welding process is the GMAW (Gas Metal Arc Welding) using a composite GMAW electrode (tubular metal cored electrode) carried out with a pulsed arc welding machine.

The robotic system was designed to have high rigidity mechanics, easy assembly and fixing on the blade surface and hassle-free operation. Low cost, light weight, portability, high positioning accuracy and repeatability are also characteristics of the resulting robotic system.

The proposed robot has the following capacities:

- Spherical topology with 5 degrees-of-freedom, 3 in the manipulator (2 rotation and 1 translation) and 2 in the wrist;
- Surface mapping with only one scanning pass;
- Embedded electronics;
- MIG/MAG Welding;
- Fixation on blades by magnetic devices or by air suction (still to be defined);
- Construction by assembling off-the-shelf parts, allowing construction of

several low-cost prototypes using an assembly manual;

– Low cost and time to design.

THE PROTOTYPE CONSTRUCTED

The robot was assembled using off-the-shelf parts found in the international market and each part was selected according to the needs and design criteria related to high rigidity to deflection, high positioning accuracy, low weight, large workspace but with short dimensions vertically to be easily inserted between blades. All parts were constructed and assembled using CAD software and the drawings can be seen below:

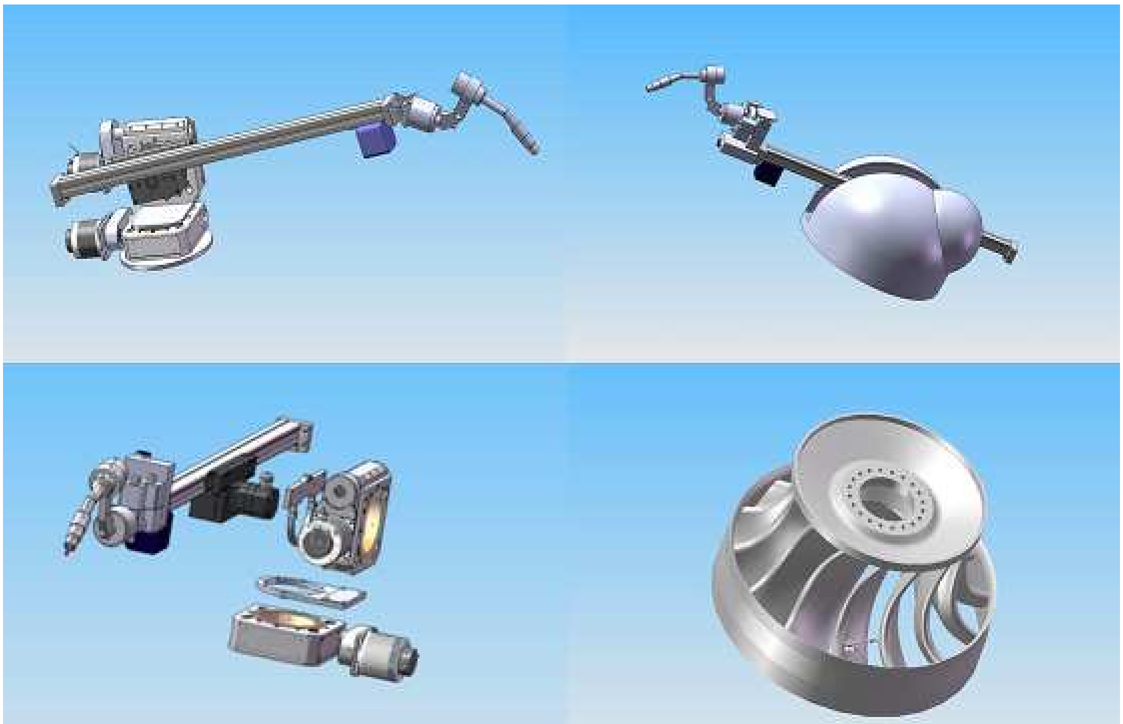


Fig. 2 – Robot prototype assembled and compared with the turbine model.

The robot constructed has weight of 30kg , workspace of 2m diameter x 60cm height and dimensions of (30 x 25 x 100 cm).

MEASUREMENT VISION SENSOR

The built-in vision sensor is based on laser scanning and active triangulation for dense surface acquisition and construction of 3-D models of the blade surface. In order to design a vision sensor capable of mapping the blade surface with high speed and accuracy, three main aspects were considered: sensor structure, image processing and calibration. The sensor structure defines the triangulation parameters and equations; the image processing detects the laser stripes and sample them, thus generating the input data for the triangulation equations; and the calibration solves the sensor parameters and is a critical procedure for the measurement accuracy.

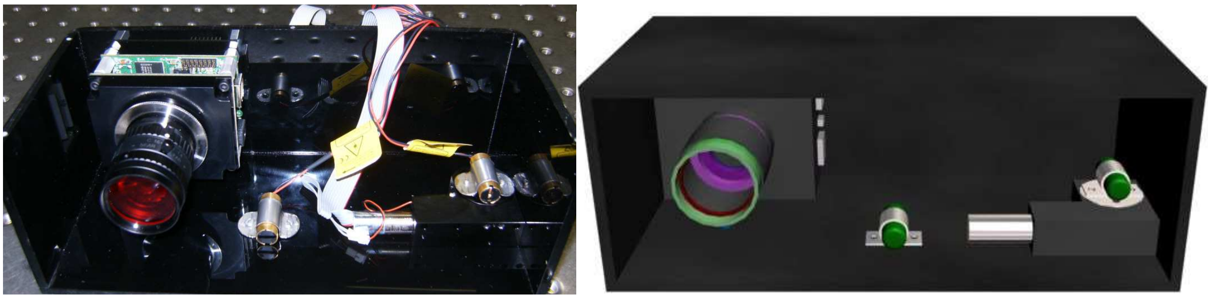
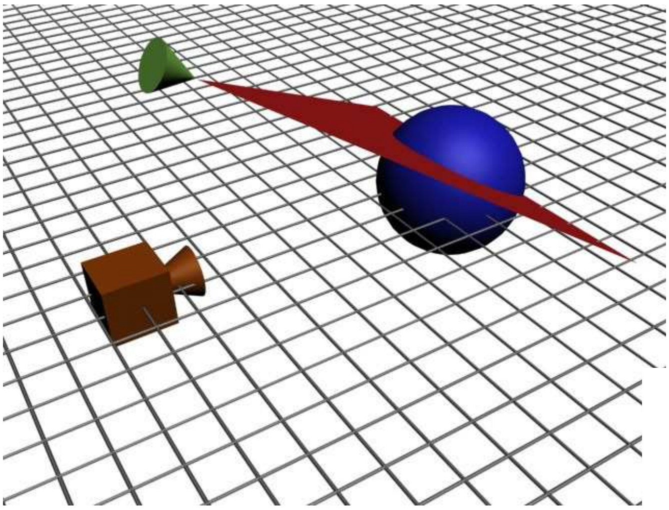
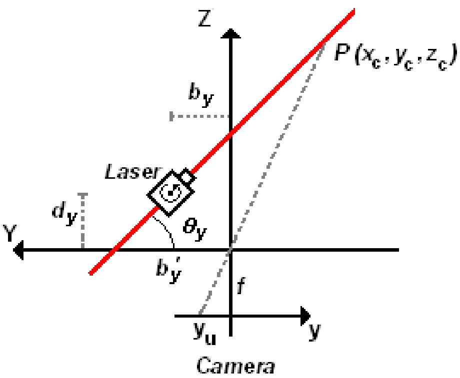


Fig. 3: Vision Sensor Design

The vision system is composed by a high resolution camera (1616x1216), 2 laser diodes (7mW) with stripe projection lens and a controlled rotary actuator for one laser diode (stepper motor). The system does not need any angular position encoder. The geometrical relation between the laser planes and the camera is determined by the sensor structure and can be mathematically modeled as in Fig. 4.





$$\begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} = \frac{b_y + d_y \cot(\theta_y)}{f \cot(\theta_y) + y_u}$$

Fig. 4: Vision Sensor Mathematical Model

Thus, with a direct relation between image coordinates of the laser stripe retrieved from the image by using image processing and the object 3-D camera coordinates, it is possible to reconstruct the damaged blade surface.

Whilst one of the laser planes is used for surface reconstruction, sweeping the whole surface while θ_y changes, the second laser plane is used solely for calculation of the sweeping angle with a higher accuracy then by using encoders, thus improving the stand-off distance in which the system can operate. An assessment of the vision system accuracy can be seen in Fig. 5.

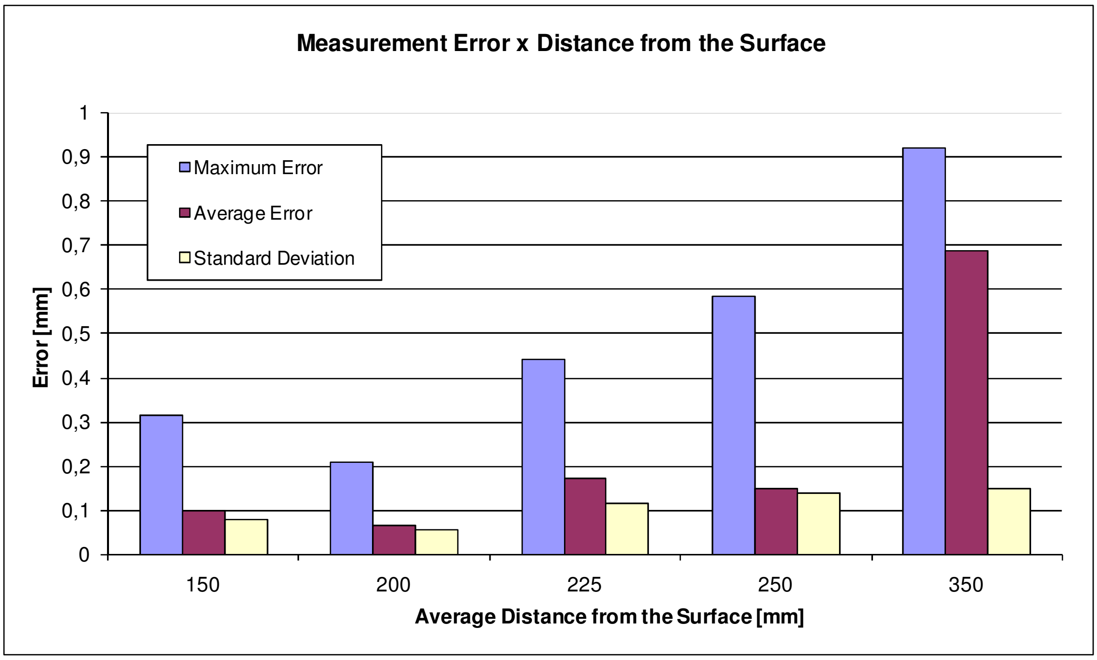


Fig. 5 – Assessment of the position accuracy when measuring the 3-D dimensions of a standard block with 50mm width in several orientations.

KINEMATIC MODEL AND CALIBRATION

A robot can be modeled as a series of links connecting its end-effector to its base, with each link connected to the next by an actuated joint.

Robot construction by assembling modular off-the-shelf parts brings about flexibility in manufacturing and allows the construction of several prototypes in the shop-floor, but also produces many sources of assembling inaccuracies. So, in order to achieve the desired accuracy, it is essential to calibrate each robotic system model to fit all the geometrical uncertainties.

Robot calibration is an integrated process of modeling, measurement, numeric identification of actual physical characteristics of a robot, and implementation of a new model that describes more precisely the robot. [7]

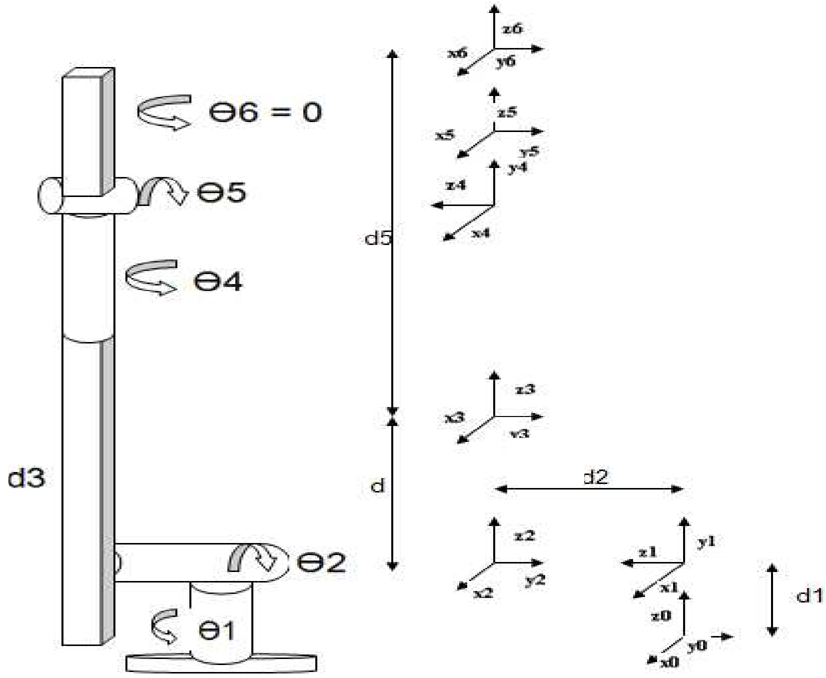


Fig. 6: Schematics of the robot kinematic model

The first step to calibrate a robotic manipulator is its kinematic modeling. The kinematic model describes mathematically the manipulator, so that robot calibration is basically a problem of fitting this non-linear model to experimental data. [8]

The implemented kinematic model specifically to allow its model calibration includes an error model to fit the actual robot errors and has to be complete, continuous and minimum [7]. In Table 1 all kinematic parameters of the robot model are shown with a proper error variable to be searched by using a parameter identification routine after several positions within the robot workspace are measured. The error variables are included in the nominal model to correct the mismatch between the actual robot and the control software, improving the robot accuracy. Translation and rotation transformations are assigned between the coordinate frames shown in Fig. 6. The kinematic model constructed has 23 error parameters that are solved by running the calibration routine.

Table 1: Robot Kinematic Model

(T_x: Translation motion in x direction; R_y: Rotation motion around y axis; δ: error to be searched)

Variable	Model
Link B	
$T_{x_b} + \delta_{Tx_b}$	0.0
$T_{y_b} + \delta_{Ty_b}$	0.0
$T_{z_b} + \delta_{Tz_b}$	0.0
$R_{x_b} + \delta_{Rx_b}$	0.0
$R_{y_b} + \delta_{Ry_b}$	0.0
$R_{z_b} + \delta_{Rz_b}$	0.0

Variable	Model
Link 0	
T_{x_0}	0.0
T_{y_0}	0.0
R_{x_0}	0.0
R_{y_0}	0.0

Variable	Model
Link 1	
$R_{z_1} + \delta_{Rz_1}$	0.0
$T_{z_1} + \delta_{Tz_1}$	110.0
$T_{x_1} + \delta_{Tx_1}$	0.0
$R_{x_1} + \delta_{Rx_1}$	90.0

Variable	Model
Link 2	
$R_{z_2} + \delta_{Rz_2}$	90.0
T_{x_2}	30.0
T_{y_2}	0.0
T_{z_2}	-100.0
$R_{x_2} + \delta_{Rx_2}$	-90.0

Link 3	
T_{z_3}	290.0
$T_{x_3} + \delta_{Tx_3}$	0.0
$T_{y_3} + \delta_{Ty_3}$	0.0
$R_{x_3} + \delta_{Rx_3}$	0.0
$R_{y_3} + \delta_{Ry_3}$	0.0

Link 4	
$R_{z_4} + \delta_{Rz_4}$	0.0
$T_{z_4} + \delta_{Tz_4}$	0.0
$T_{x_4} + \delta_{Tx_4}$	0.0
$R_{x_4} + \delta_{Rx_4}$	90.0

Link 5	
R_{z_5}	0.0
$T_{x_5} + \delta_{Tx_5}$	0.0
$T_{y_5} + \delta_{Ty_5}$	0.0
$T_{z_5} + \delta_{Tz_5}$	0.0
R_{y_5}	0.0
R_{x_5}	0.0

THE ROBOT CONTROLLER

The robot controller is built with reconfigurable architectures (*Field Programmable Gate Arrays*). FPGA's are programmable logic devices that permit the implementation of digital systems. They provide arrays of logical cells that can be configured to perform given functions by means of configuration bitstream. The bitstreams are generated by a software tool, and usually contains the configuration information for all the components. Configuration of the FPGA can be realized by using several design/synthesis tools provided by companies such as Altera [9] and Xilinx [10]. The circuit can be described using a high level description language as VHDL or Verilog [11]. The tool makes the synthesis of the description file producing a binary configuration file (*bitstream* file). This file is used to configure the FPGA device.

FPGAs permit to implement algorithm directly in hardware instead of in software (for instance, using microcontrollers). Implementation in software has limitations due to the sequential nature of von Newmann architectures that run the software model. In contrast, in FPGA implementations the potential of parallelism can be explored in order to improve the performance of the system. Moreover, the flexibility of these devices permits to configure (reconfiguration operation) the system even in real time.

Reconfigurable systems are composed of a microcontroller and a FPGA working jointly. In this case one part of the system can be running in software (in the microcontroller) whereas the other part can be implemented in hardware (in the FPGA). In general, reconfigurable systems can be designed using hardware-software co-design approach which specifies methodologies in order to determine the system parts being implemented in software and hardware. This partitioning can be made taking into account a function cost that tries to optimize some circuit characteristic such as area, performance and power consumption of the system.

Figure 7 describes the overall architecture of the robot controller, which is composed of an FPGA embedded microprocessor (such the NIOS), an embedded bus (e.g. the Avalon bus) and other modules. The memory module is used for storing a supervisory program that is connected to the main bus jointly with the kinematics and dynamics controller modules. Differently of other proposed approaches [12], the kinematics and dynamics modules are capable to implement float point operations directly in hardware. Trigonometric operations such as tangent, sine, among other are implemented using the IC algorithms [13].

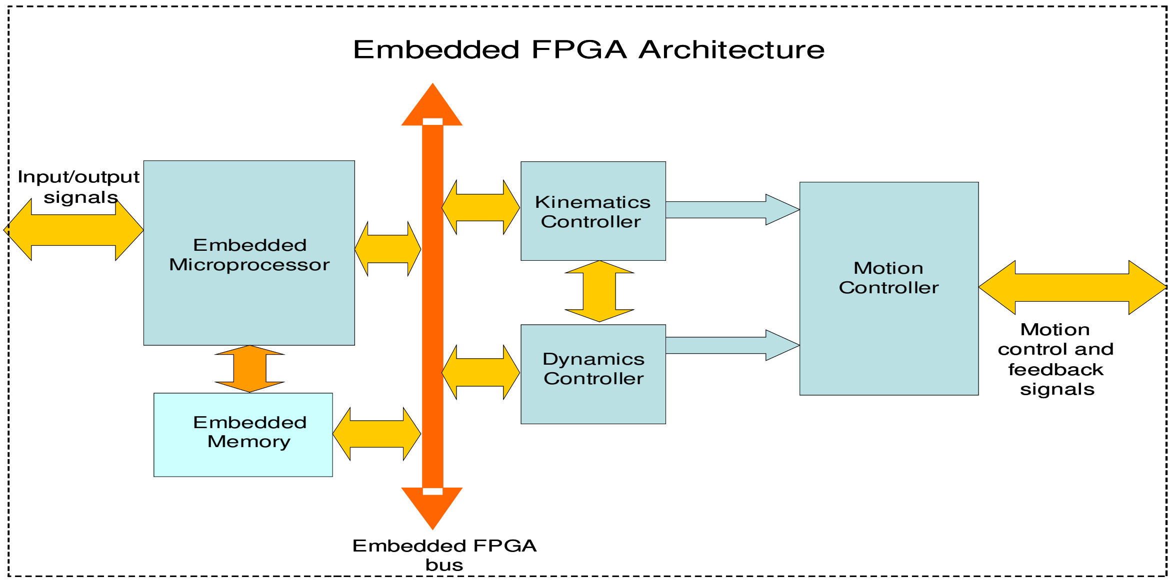


Fig. 7: the overall FPGA embedded architecture for the robot controller

ACKNOWLEDMENTS

ELETRONORTE (Electrical Power Plants of the North of Brazil) and FINATEC (Scientific and Technological Enterprises Foundation) are thanked for their financial support and collaboration. Our gratitude is especially conveyed to the staff of ELETRONORTE for their technical support and interest.

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