Project N°: IST-1999-13109
Acronym: REHAROB

LIST OF SELECTION CRITERIA AND SPECIFICATION OF THE SELECTED INDUSTRIAL ROBOT

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RÈSUMÈ

Deliverable 3 summarizes how the industrial robots were selected for the robot mediated physiotherapy. Not only the robots but also the manufacturer was selected and linked to the REHAROB project through a subcontract.
Selected industrial robots: IRB 140 & IRB 1400.
Selected robot manufacturer: ABB Automation – Robotics Systems.

CONTENTS

1 Introduction

This project focuses on developing a system for upper limb motion therapy methodology for patients with neuro-motor impairments. The therapy will be driven by industrial robots utilising intelligent identification of the required physiotherapy motions. This will be achieved by a robotic rehabilitation system called REHAROB.

In order to select adequate robots for the physiotherapy the following requirements have to be considered:

- technological requirements (workspace, speed, payload, control, etc.) for the recommended physiotherapy exercises,
- design requirements like communication with other elements in the cell, and a feasible cell layout,
- safety requirements,
- legal requirements: medical certification,
- economics requirements.

All of the above listed requirements form the scope of subsequent tasks and deliverables like:

- Deliverable 7: Analysis of the upper limb motion, impairments, and motion therapies used and improvements for the impairment rehabilitation,
- Deliverable 9: Technical documentation of the non-commercial part of the 3D motion therapy monitoring system,
- Deliverable 11: Methods and equipment for an improved upper limb motion therapy including the application package for the submission to the Ethics Committee,
- Deliverable 15: Assessment and evaluation of the REHAROB cell for motion terapies,
- Deliverable 11: Specification of the industrial robot adapted to the REHAROB cell.

It was decided on the partner meeting held in Tübingen (D), on 13-14 July 2000 that this deliverable should not give a detailed account on these issues although a significant progress has already been achieved. Instead, it gives proper evidence that all the listed requirements have been considered during the selection of the industrial robots.

For the definition of the requirements the following steps were taken:

1. Collecting users requirements and engineering solutions through interviews, from the literature, and from the World Wide Web
2. Analysis of the relevant robot, safety and medical equipment certification procedures
3. Definition of requirements for REHAROB
4. Market analysis of industrial robots
5. Opening a tender: contacting 18 industrial robot manufacturers
6. Feedback/quotations from 6 robot manufacturers
7. Preselection of robot manufacturers
8. Detailed evaluations of the received quotations
9. Selection of the industrial robot(s)
10. Specification of the industrial robot(s)

2 Definition of the requirements for the industrial robots and the robot manufacturer

2.1 Collecting users requirements and engineering solutions

The main objective of the Reharob project is to develop a robotic system for upper limb motion therapy for patients, who have hemiparesis due to central nervous system damage. In the analysis phase of the project the possible physiotherapy exercises have been collected so as to demonstrate the physiotherapist's work. The robot (or robots) will be required to execute selected exercises from this catalogue (available on the project Web page: http://reharob.manuf.bme.hu).

2.1.1 Simulation based conceptual design of the REHAROB cell

Due to the high 3D complexity of the physiotherapy exercises it was decided that any decision on the selection of the active therapy devices: industrial robot(s) (See Figure 1!), F/T sensors (See Figure 1!), orthosi(e)s (See Figure 2 and Figure 3!) that connect the patient arm with the robot(s), therapy bed/chair (See Figure 5!) must be verified with simulation.

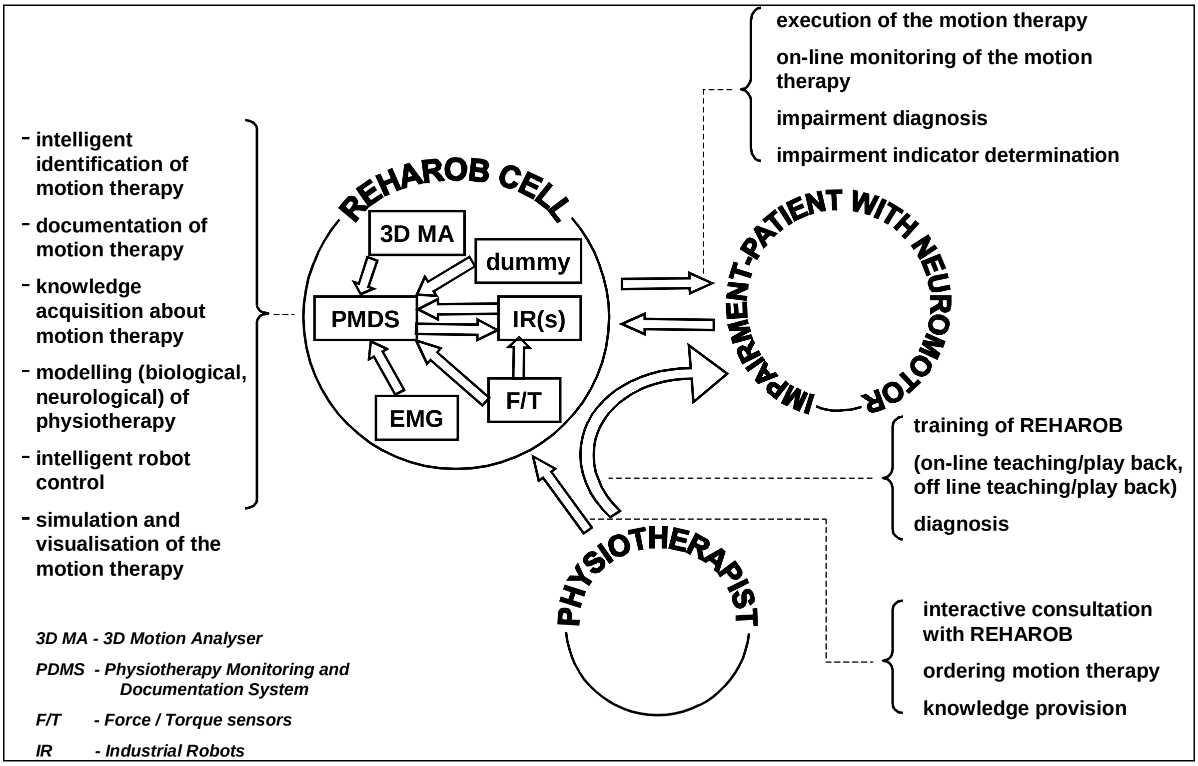


Figure 1 The REHAROB triangle

For the simulation the IGRIP® advanced 3D robot simulation tool of Deneb Robotics Inc. was selected because

- through built in CAD functionality the non-standard elements of the REHAROB cell including the Virtual Reality mannequin can be modelled
- through definition of the upper limb kinematics it is capable for the simulation of the physiotherapy exercises

- through reading data of the 3D Motion Analyser simulation of the physiotherapy exercises can be automated
- all existing industrial robots can be loaded from libraries
- it is capable for detection of constraint violation such as:
  - joint range limits
  - joint velocity limits
  - joint acceleration limits
  - joint force or torque limits
  - detection of the collision of any rigid body with another rigid body

The Virtual Reality mannequin was created on anthropometrical consideration described in Task 1.1 reports which will be parts of *Deliverable 7: Analysis of the upper limb motion, impairments, and motion therapies used and improvements for the impairment rehabilitation*. (The built in human VR models cannot be used because they satisfy the needs of ergonomic modelling but not the needs of the biomechanical modelling.) The REHAROB mannequin currently consists of simple Euclidean solids which the human kinematics and range of motion (ROM) are associated with. Its current kinematic structure has 5 DOF including only rotational kinematic pairs (See Figure 2!) Later two additional DOF's will be added to the shoulder to allow the spherical motion of the humerus. Dynamic properties of the biomechanical model will also be added later.

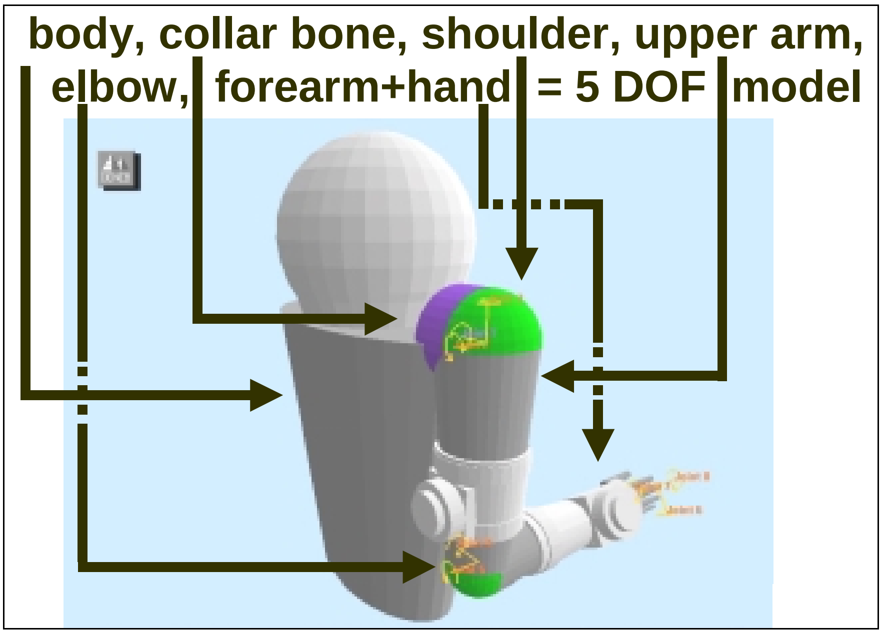


Figure 2 Modelling the upper limb in IGRIP®

Biomechanical considerations have led to the decision that two robots have to be used for a correct physiotherapy, i.e. to cope with the problem of axes misalignments between the biomechanical and the therapeutic machine kinematic axes, which so many predecessor researches failed to solve correctly. Robot1 has to move the upper arm and robot 2 has to move the lower arm. Both robots will be connected to the patient's arm by means of specially designed orthoses. Figure 2 shows simplified models of the lower and upper arm orthoses while Figure 3 shows the conceptual structure of the lower arm orthosis.

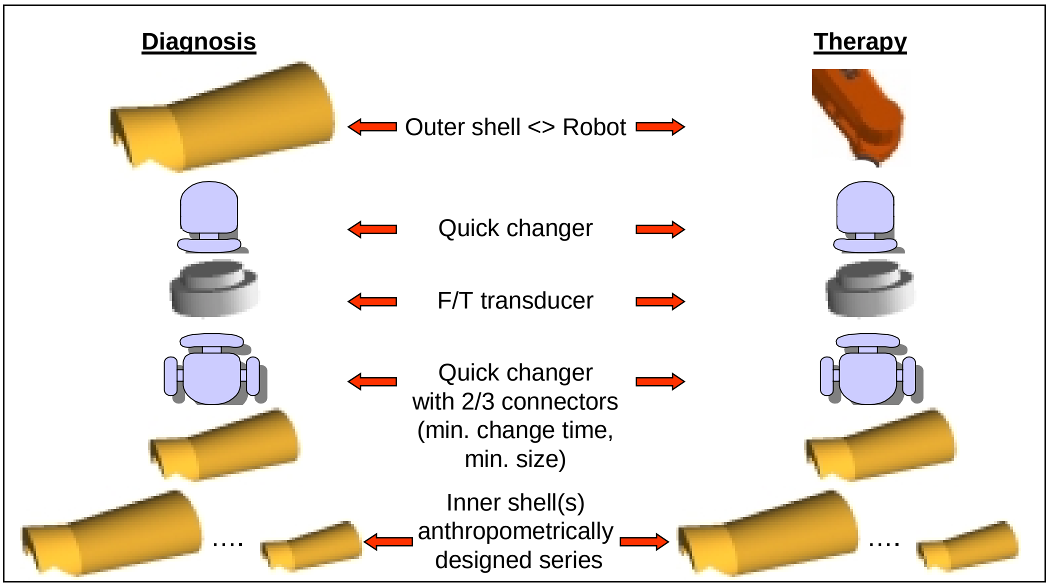


Figure 3 Conceptual design of the lower arm orthosis

To start the conceptual design of the REHAROB cell the upper arm dimensions of the tallest and heaviest patient were defined first (See Figure 4!). The upper limb was scaled up with using a regression tool developed in Task 1.1.

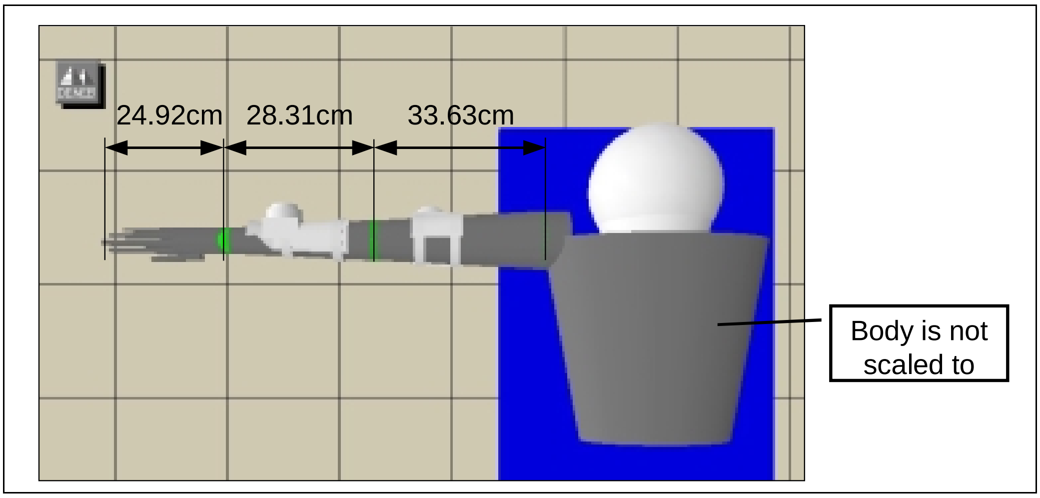


Figure 4 Extremist REHAROB patient: 190cm tall, 150kg weight

Due to the limitations of time and resources available for the robot selection VR simulations were prepared only for the most workspace and mobility demanding exercises: N°29, N°37, and N°40 (See Figure 5!). Each exercise should be feasible in 8 arrangements: in lying and in sitting positions of the patient, for a left arm patient and for a right arm patient, and with an orthosis with the connector up and with an orthosis with the connector down. Later, for the detailed design of the REHAROB cell this manual simulation technique will be automated: motion measurements recorded in Task 1.2 will be fed into IGRIP® for simulation.

Following the arm movement simulations the robot should be inserted into the simulation environment by connecting it to the orthoses. In the simulation we follow just an opposite strategy to the real therapy: the patient's arm moves the two robots by applying mechanical constraints at the contacts. The two robots should be inserted into the Virtual Environment (VE) not to collide with any other body in the VE but be able to follow the arm movement throughout the exercise.

This procedure is called layout design in engineering terms. The design requirements for the layout design of the REHAROB cell were:

- consider only 3 elements: robot1, robot2, bed(chair)
- fix(screw down) all elements in the VE
- be able to adapt to physiotherapy in lying/sitting positions
- be able to adapt to left arm/right arm physiotherapy
- allow teach-in play back for the physiotherapist
- allow 1 rotational adjustment DOF to the bed
- allow 1 translational adjustment DOF to the bed
- allow 2 translational adjustment DOFs to the bed

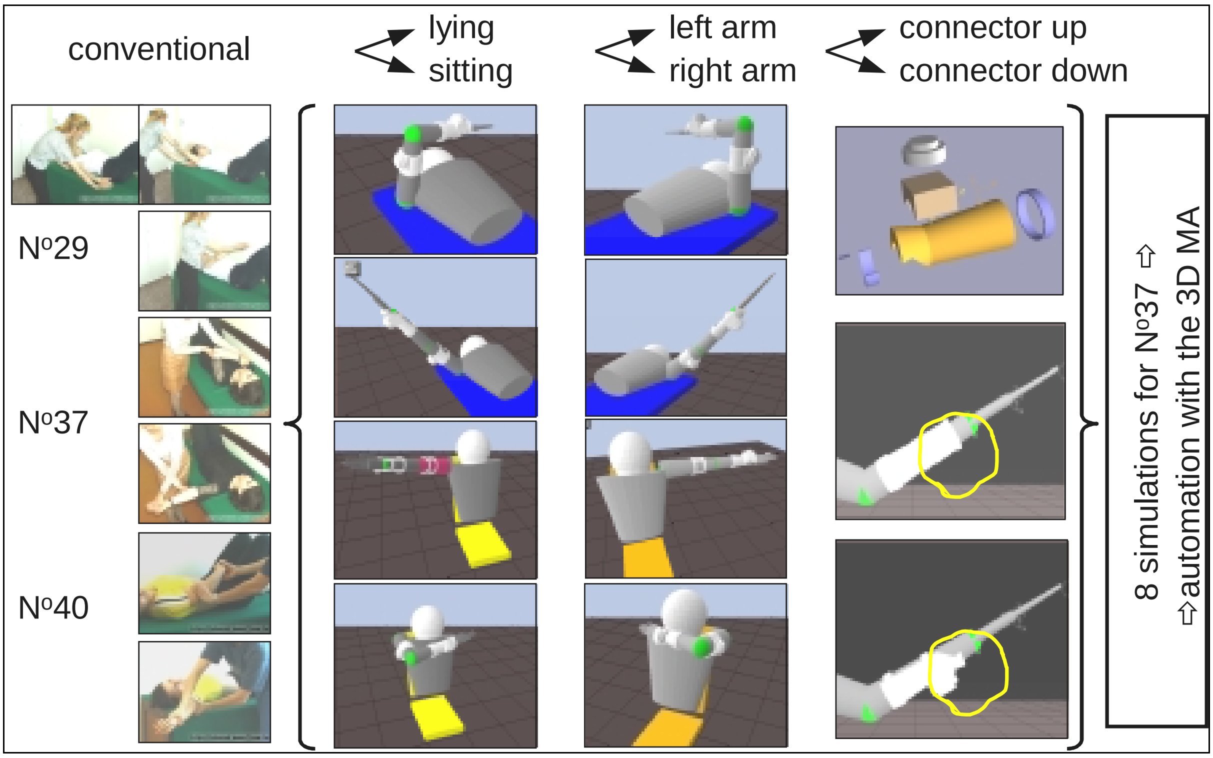


Figure 5 Simulation of selected exercises

It is obvious that with a special multi segment bed/chair the design requirements can be satisfied if left arm patient is allowed to lie/sit just facing to as right arm patient is allowed to sit/lie. For simplicity this case was modelled with 180^{o} turn of the bed.

Another simple case is when two beds/chairs located in right angles to each other are used for the left arm and for the right arm therapy respectively. For simplicity this case was modelled with 90^{o} turn of the bed.

Other cases may require real physical adjustment of the bed/chair so were excluded from the simulation.

Figure 6 shows how teach-in and play back is conceptualised for REHAROB. (The PUMA 560 type industrial robots are used only for illustration.)

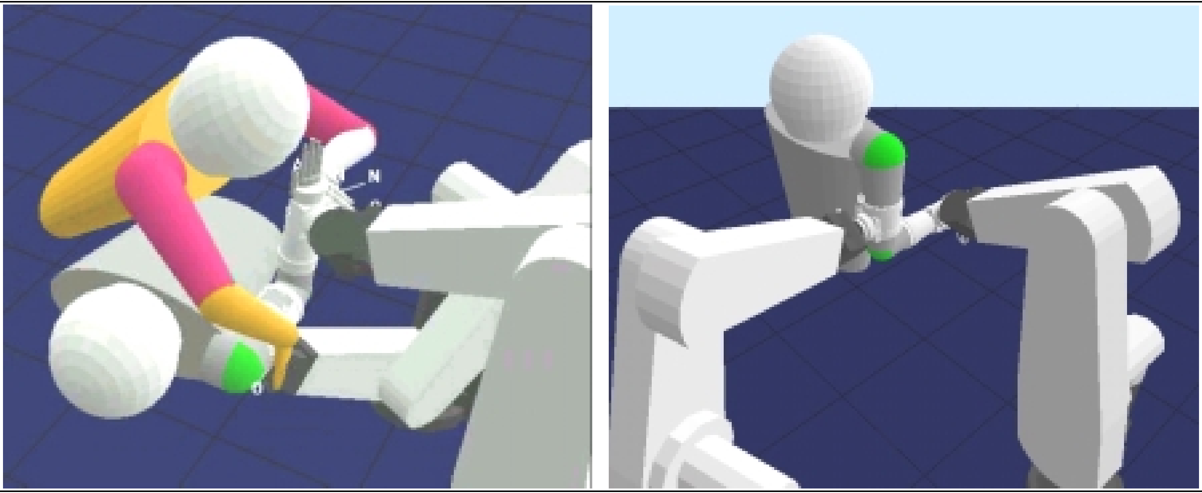
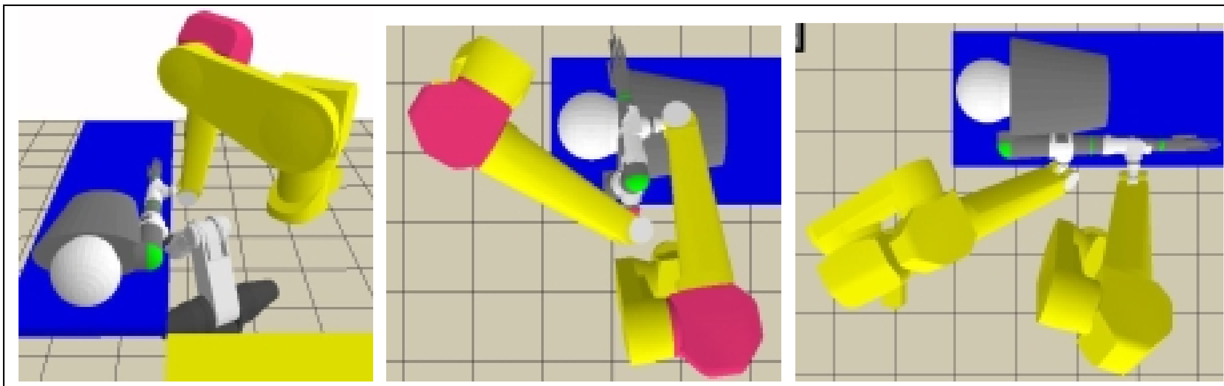


Figure 6 Teach-in (left) and play-back of the physiotherapy in REHAROB

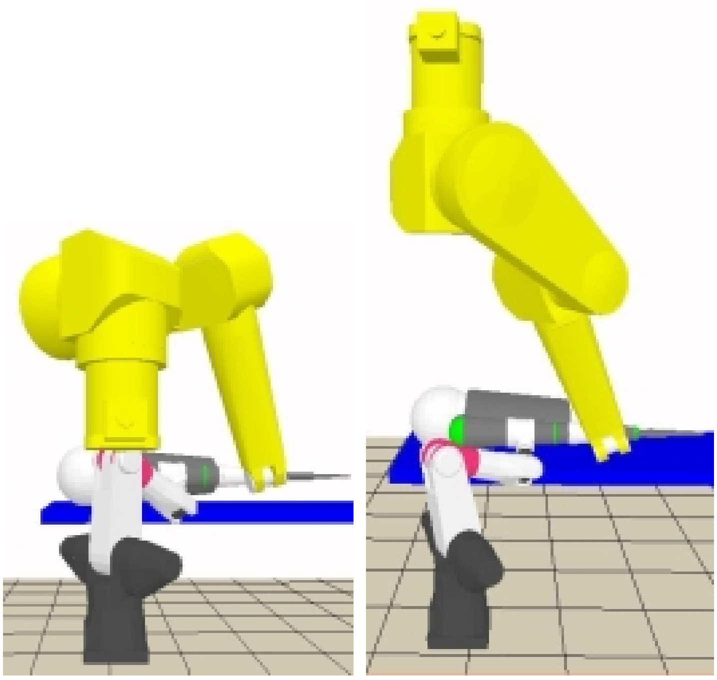
If the two robots are based in the same plane then only 3 layouts can be considered as it is shown in Figure 7. All of the shown layouts have been rejected because the selected exercises are impossible to execute without intersection of robot-robot, robot-patient arms during therapy..



turn of 90^{o} turn of 180^{o} turn of 180^{o}

Figure 7 Common plane layouts: rejected

The same happens in the case when one robot is installed above the other (See Figure 8!) This figure shows the layout found only successful: two robots are above each other and the upper one is in hanging configuration. The quoted robots were tested for the selected exercises in this layout.



turn of 180° turn of 180°

Figure 8 One above another layouts: left is rejected, right is accepted

Conclusions drawn from and decisions made on the basis of the literature survey, end user requirements analysis and Virtual Reality simulations:

a) when developing a therapeutic machine for the upper limb the most difficult issue is to cope with the kinematics of the 5DOF shoulder complex. In REHAROB therefore, unlike at other therapeutic machines we will allow 6DOF movement of the upper arm hence not constrain any movement of the shoulder complex. An industrial robot of 6DOF will be necessary to move the upper arm. The robot should be connected to a suitable upper arm orthosis.

b) the lower arm will be moved also by a 6DOF industrial robot. From biomechanical point of view this is not necessary as only 2DOFs: elbow flexion-elbow extension and pronation-supination are added to the DOFs of the upper arm resulting in a 7DOF upper arm model. However, to overcome the design and manufacturing problems of a 2DOF powered orthosis it was decided to use a second 6DOF robot to move the lower arm. The robot should be connected to a suitable lower arm orthosis.

c) physiotherapy of the hand is excluded from the scope of REHAROB due to the numerous DOFs of the hand. During the robot mediated therapy the hand should be kept in an inclined reflex inhibition position that can be adjusted to the patient through the hand support of the lower arm orthosis.

d) literature survey [Valleggi et al, 1996], [Buckley, 1996], [LaSatyo, 1995] and measurements at BUTE have concluded that resultant force and torque at connectors of the upper and lower arm orthoses will not exceed 123N and 65 Ncm during the therapy of hemiparetic patients. Taking into consideration of the allowable 100-1000% overloading of industrial robots when accuracy and high speed is not required 5 kg load capacity industrial robots will be required for the physiotherapy.

e) commercial variable 3D motion physiotherapy machine with the aim of fully and totally replace the physiotherapist in exercise and active physiotherapy of the arm of spastic hemiparetic patients is not known.

f) there are several commercially available therapeutic machines (Kintrex, Artromot, EX N' Flex, Biodex, Cybex, Kinetec, Danniflex, etc.) for the Continuous Passive Movement

(CPM) or fixed trajectory exercise ([Dixon, 1985], Constant Rate Velocity Change Motion Controller) therapy of hemiparetic patients

g) there are some custom made commercially available [Engen & Spencer, 1969], [Snelson et al, 1961], [Leonard et al, 1989], [Hokken et al, 1993] or post-research phase [Sauter et al, 1989], [Romilly et al, 1994], [Dixon, 1985] powered and passive orthoses to assist the motion of the patient's arm. These are not considered as therapeutic machines.

h) there are prototype physiotherapy machines with the aim of fully and totally replace the physiotherapist in the exercise and active physiotherapy of the arm of spastic hemiparetic patients. These are: powered orthosis [Johnson et al, 1998], custom made SCARA robot [Hogan et al, 1992], [Hogan et al, 1995], [Krebs et al, 1999] combination of passive arm support and industrial robot [Lum et al, 1999].

i) industrial robots are technologically capable for force control. Vast majority of the industrial robots are position controlled, there are however some applications (painting, machining, assembly) in which industrial robots are controlled by force sensory input. REHAROB can benefit from these applications but will need additional developments from the robot manufacturer. Theoretical foundations for the various force control approaches exist and already implemented in non-industrial robots: space robots, research robots, tele-robotics, haptic devices.

2.2 Analysis of the relevant robot, safety and medical equipment certification procedures

The following robot, safety, and medical equipment certification related standards and norms have been reviewed:

Robot standards:

EN ISO 8373:1994 Manipulating industrial robots -- Vocabulary
EN ISO 9283:1998 Manipulating industrial robots -- Performance criteria and related test methods
EN ISO 9787:1998 Manipulating industrial robots – Coordinate systems and motions
EN ISO 9946:1999 Manipulating industrial robots -- Presentation of characteristics
EN 775 ISO 10218:1992 Manipulating industrial robots -- Safety (Ed. 1; 10 p; E)

Safety standards:

EN 292-1 Safety of machinery, basic terminology
EN 292-2 Safety of machinery, technical principals / specifications, emergency stop
EN 418 Safety of machinery, emergency stop equipment
EN 563 Safety of machinery, temperature of surfaces
EN 614-1 Safety of machinery, ergonomic design principles
EN 60204 Electrical equipment for industrial machines
prEN 574 Safety of machinery, two-hand control device
prEN 953 Safety of machinery, fixed / movable guards
prEN 954-1 Safety of machinery, safety related parts of the control system
EN 50081-2 EMC, Generic emission standard
EN 55011 Class A
EN 50082-2 EMC, Generic immunity standard
EN 61000-4-2 Electrostatic discharge immunity test
EN 61000-4-3 Radiated, radio-frequency. Electromagnetic field immunity test
ENV 50204 Radiated electromagnetic field forming. Radio telefones immunity test
EN 61000-4-4 Electrical fast transient / burst immunity test

ENV 50141 Conducted disturbances inducted by radio-frequency fields, immunity test
IEC 204-1 Electrical equipment of industrial machines
IEC 529 Degrees of protection provided by enclosures

Medical device standards:

Council Directive 93/42/EEC of June 1993 concerning medical devices
EN IEC 60601-1 Safety of medical electrical equipment, Part l: General requirements for safety

Conclusions drawn from the analysis:

a) there is an approach difference between the listed robot or safety standards and the medical device standards. Robot and safety standards are low-level technical standards while medical device standards are high level generic standards.
b) industrial robots fulfil all robot and safety standards for industrial applications, which was the major reason to select industrial robots for the robot mediated physiotherapy.
c) industrial robots on the other hand need to be certified as medical devices. This is always a specific application dedicated procedure when a certified body issues the CE mark for the medical device. The REHAROB cell will definitely belong to the device Class 2b as physical contact between the therapeutic machine and the patient occurs. At the moment it cannot be precisely forecasted what mechanical, electric and control safety measures and devices will be required for the REHAROB cell, so the robot manufacturer will be required to collaborate with the REHAROB project throughout its full duration and provide the REHAROB cell with product support after termination of the project.
d) according to Council Directive 93/42/EEC the manufacturer of the medical device has to apply for the certification. In case of the REHAROB project all project wide developments have to be admitted and approved by the robot manufacturer who as legal entity shall apply for the certification.
e) members of the REHAROB project believe that service robotics including medical robotics applications could benefit from the mass of standards referring to industrial robots. In order to formulate a technical standard on service (including medical) robotics BUTE as coordinator of the REHAROB project has made an official enquiry to the Hungarian Standardization Body. The enquiry was about to initiate the change/creation of the legal, standard and safety basis for the use of industrial robots in human rehabilitation. It is thought that EN 775 ISO 10218:1992 Manipulating Industrial Robots-Safety standard should be harmonized with EN/ISO standards referring to medical equipment applications (93/42/EEC). BUTE was informed that to initiate negotiations about a New Work Item Proposal needs at least 5 supporting votes of National Bodies. The robot manufacturer will be required to lobby for the votes of National Bodies of the EU and associated states.

3 Requirements for the industrial robots

The analysis briefly outlined in Section 2 has resulted in the following list of requirements for the industrial robots:

PERFORMANCE CHARACTERISTICS (according to EN ISO 9946:1999, EN ISO 9946:1999and to EN ISO 9283:1998):

- arm type: jointed, or polar, or cylindrical
- load capacity: max. 6-7 kg
- number of axes: min 6
- speed: expected to be low – not crucial factor for REHAROB
- repeatability: expected to be medium – not crucial factor for REHAROB
- accuracy: expected to be medium – not crucial factor for REHAROB
- acceleration: expected to be medium or high – subject to detailed simulation with the quoted robots
- workspace: robot 1: reach of max 1 m, robot 2: reach of max 2 m
- weight: as less as possible
- vibration: low – it is recommended not be sensitive to external excitation
- drive system: electric

CONTROL/PROGRAMMING CHARACTERISTICS:

- the robot will be integrated with a PC which will be used also for programming and monitoring of the robots, this PC should be able to communicate with the robot controller
- spline interpolation
- 6 DOF F/T measurement at the end effector or at the joints: <u>very important</u>
- force-position (compliance) control: <u>very important</u>, what bandwidth is available?
- on-line and off-line programming
- is teach-in play-back programming technology available?
- path correction facilities,
- on-line program correction
- high-level structured object-oriented programming language

SAFETY SYSTEMS

In addition to the safety systems required by the EN 775 ISO 10218:1992 the selected industrial robot will be certified during the project by

- Medical Devices Directive 93/42/EEC
- EN IEC 60601-1 Safety of medical electrical equipment, Part l: General requirements for safety

Very strong preference will be given to an industrial robot that has already obtained the CE mark according to 93/42/EEC Class 2b and EN IEC 60601-1, i.e. it can contact humans.

CAxx and SIMULATION SUPPORT:

- support of CAD model, postprocessor for programming in simulation environment, sensor modelling, kinematics and dynamics modelling
- is there a standalone 3D simulation environment for the robot offered available?
- is the robot offered available in or attachable to commercial simulation packages like RobCAD®, IGRIP® ,RobSim®, Workspace®, etc?

PLEASE LIST THE MOST RELEVANT INDUSTRIAL OR SERVICE APPLICATIONS FOR THE INDUSTRIAL ROBOTS YOU OFFER US:

- ……………
- ……………
- ……………

OTHER CHARACTERISTICS:

- clean room application
- easy cleaning
- is optional covering possible?

4 Requirements for the Robot Manufacturer

The analysis briefly outlined in Section 2 has resulted in the following list of requirements for the robot manufacturer:

REQUIREMENTS FOR THE ROBOT MANUFACTURER

- the robot and the controller should be a serial product of annual volume not less than 100 pieces,
- sell or lease the two robots and the controller to the REHAROB consortium in a discount price,
- join the REHAROB consortium as a subcontractor: contribution to the project for 100000 EUR can be subcontracted to the robot manufacturer
- willingness to lobby for the modification of safety standards to allow contact between humans and the robot,
  (Most problematic clause of EN 775 ISO 10218:1992 can be found in Section 4.1 on p.3: "*the absence of persons in the safeguarded space during automatic operation*." In the case of robotized rehabilitation of patients this cannot be kept.)
- willingness to proceed with/support a certification procedure enforced by 93/42/EEC Class 2b and EN IEC 60601-1
- experience in force-position control for industrial tasks
- reference to service robot applications
- reference to medical robot applications

5 List of contacted robot manufacturers

The list contains all the industrial robot manufacturers identified by the REHAROB project. Cells of the robot manufacturers contacted by the REHAROB project are shaded.

COMPANY	HOME PAGE	ADDRESS
ABB	http://www.abb.com/	Asea Brown Boveri Kft Magyar Gabor 9027 Gyor, Budai ut 2. Tel: 96-512 951 Fax: 96-512 958 gabor.magyar@huabb.mail.abb.com
AEA	http://www.aeat-prodsys.co.uk/subdivisions-div/NEAT1.html	
ARRICK	http://www.robotics.com/	
BOSCH	http://www.boschautomation.com/	
CLOOS	http://www.cloos.de/uk/produkte/roboter/index.html	
COMAU	http://www.robosiri.it/CMAU.htm http://www.bra-automation.co.uk/feb99.txt	COMAU Robotica Strada Orbassano 20/22 10092 Beinasco - Torino (Italia) Tel. 011.6849.111 Telefax 011.3971468 e-mail Uff. Marketing: vigna@comau.com
CRS	http://www.crsrobotics.com/products/index.html?pro_y2k_fs.html http://www.crsrobotics.se/	CRS Robotics Nordic AB Science & Technological Parks 223 70 Lund Sweden Telephone: +46 (0)46-286 86 20 Fax: +46 (0)46-286 86 22 info@crsrobotics.se
ESHED	http://www.eshed.com/	ESHED 472 Amherst St, Nashua, NH 03063 USA tel: 603-579-9700 fax: 603-579-9707 http://www.eshed.com/form99.htm

FANUC	http://www.fanucrobotics.com/	FANUC Robotics Europe Zone Industrielle L-6468 Echternach Grand-Duché de Luxembourg Tel.: (352) 72 77 77-1 Fax: (352) 72 77 77-403 FORM
HITACHI	http://www.hitachi.com/products/industrial/indrobots/index.html http://www.hitachi-eu.com	Hitachi, Ltd. (Hitachi Corporate Office, Europe) Avenue Louise 326-BTE 11 1050 Bruxelles Belgium Tel: <32> (2) 643-4888 Fax: <32> (2) 640-0898 FORM http://www.hitachi.com/contact/index.html
ISE	http://www.ise.bc.ca/robot1002.html	ISE 1734 Broadway Street, Port Coquitlam, B.C. CANADA V3C 2M8 Tel: 604.942.5223 Fax: 604.942.7577 Email: info@ise.bc.ca Web: www.ise.bc.ca
KAWASAKI	http://www.kawasakirobot.com/	Kawasaki Robotics (UK) Limited Greengate, Middleton Manchester M24 1SA United Kingdom Phone: 0161 956-5400 Fax: 0161 956-5404 kathy@kri-us.com
KUKA	http://www.kuka.de/	KUKA Roboter GmbH Postfach 431364 D-86073 Augsburg Blücherstraße 144 D-86156 Augsburg Phone: +49-821-797-4000 Fax: +49-821-797-1616 e-mail: info@kuka-roboter.de

LABMAN	http://www.zebra.co.uk/labman/	
MANUTEC		
MITSUBISHI	http://www.meau.com/	MITSUBISHI 200 Cottontail Lane Somerset, NJ 08873 USA Tel (732) 560-4500 Fax (732) 560-4535 Email: eastsales@meau.mea.com
MOTOMAN	http://www.motoman.com/	Motoman, Inc. 805 Liberty Lane West Carrollton, Ohio 45449 USA (937) 847-3300 info@motoman.com farkasat@westel900.net
NACHI	http://www.nachirobotics.com/ http://www.nachi.com.br/	Nachi Robotic Systems Europe GmbH (NRSE) Stuifenstrasse 50 D-74385, Pleidelsheim Germany Tel: 49.7144.80350 Fax: 49.7144.803520 FORM
NORMADIC	http://www.robots.com/	
OTC-DAIHEN	http://www.otc-daihen.com/	OTC-DAIHEN Dynamic Robotics Division 761 Crossroads Ct. Vandalia, OH 45377 USA Tel: (937)454-9660 Fax: (937)454-9661 DRD@otc-daihen.com
OXIM	http://www.oxim.co.uk/	Oxford Intelligent Machines Ltd 12 Kings Meadow, Ferry Hinksey Road Oxford OX2 0DP United Kingdom Tel: (44) 1865 204881 Fax: (44) 1865 204882 "Tim Jones" tim@wynford.fsbusiness.co.uk

PANASONIC	http://www.pfae.com/products/robots.php3	Panasonic Factory Automation Europe A Division of Panasonic Industrial Europe GmbH Winsbergring 15 D - 22525 Hamburg Germany Phone: 040 - 85 38 62 75 Fax:040 - 85 38 62 18 FORM: http://www.pfae.com/contact/contact.php3
PEUGEOT		
REIS	http://www.reisrobotics.com	Reis Robotics Industriegebiet an der B 426 D-63785 Obernburg Germany Tel. ++49-6022-503-0 Fax ++49-6022-503-110 websales@reisrobotics.de www.reisrobotics.cz
SCHILLING	http://www.schilling.com/manipulator.html	
SEIKO	http://www.seikorobots.com/	
SEF ROBOTER		
STÄUBLI	http://www.staubli.com/Staubli/Home.nsf/HomePage?OpenForm&Language=GB	STÄUBLI AG Seestrasse 240 CH - 8810 Horgen SWITZERLAND Tel : +41.1.728.61.11 Fax : +41.1.728.66.34 E-mail : info@staeubli-ag.ch
YAMAHA	http://www.yamaharobotics.com/	

The following table summarises the results of the tender:

Quotations were received from	**Interested but failed/missed to quote suitable robots**	**Disinterested**	**No reply from**
ABB MOTOMAN REIS STÄUBLI	ESHED FANUC KAWASAKI OXIM	KUKA	COMAU CRS HITACHI ISE MITSUBISHI NACHI OTC-DAIHEN PANASONIC SEF ROBOTER

None of the four quotations met fully the stated requirements so BUTE entered into further personal negotiations with ABB, MOTOMAN and STÄUBLI. Only REIS was excluded from the negotiations as no commitment to collaboration arrived with the quotation.

6 Comparison of the quotations of the pre-selected robot manufacturers

During personal multi round negotiations all quotations and commitments of the preselected robot manufacturers were finalized. Evaluation of the quotations was made with using a score system. If a requirement is fulfilled than it is indicated with a tick and the score associated with the requirement item at the upper left index is added to the total of the robot manufacturer. If the quotation does not meet the requirement than a cross is shown at the manufacturer’s column and no scores are added to the manufacturer.

The table below compares the quotations of the three pre-selected industrial robot manufacturers:

Requirement	**Stäubli**		**ABB**		**Motoman**	
Performance:						
robot 1: reach<1m:	RX 60LB 		IRB-140 		UP6 	
[1]arm type, DOF	jointed, 6 DOF	☑	jointed, 6 DOF	☑	jointed, 6 DOF	☑
[1]load capacity	2.5 kg	☑[1]	5 kg	☑	6 kg	☑
[1]max reach[2]	865 mm	☑	810 mm	☑	1373 mm	☒
robot 2: reach<2m:	RX 90BL 		IRB-1400 		UP6 	
[1]arm type, DOF	jointed, 6 DOF	☑	jointed, 6 DOF	☑	jointed, 6 DOF	☑
[1]load capacity	3.5 kg	☑[1]	5 kg	☑	6 kg	☑
[1]max reach[2]	1185 mm	☒	1440 mm	☑	1373 mm	☑
[1]total[3] list price:[4]	EUR 108,700	☒	EUR 83469	☒	EUR 67260	☑
[1]REHAROB price:[5]	EUR 72,000	☑	EUR 71000	☑	EUR 67260	☑
[1]appearance	nice looking	☑	too industrial	☑[6]	nice looking	☑

[1] Based on the information of the manufacturer the robot can be loaded up to 20-24 kg if nominal accuracy and nominal speed are not required

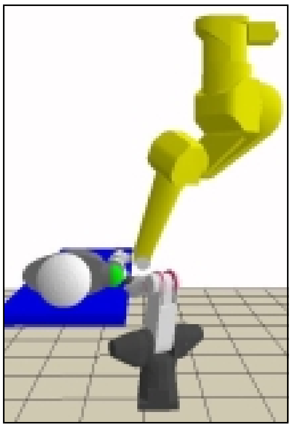
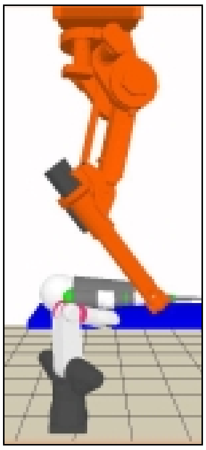
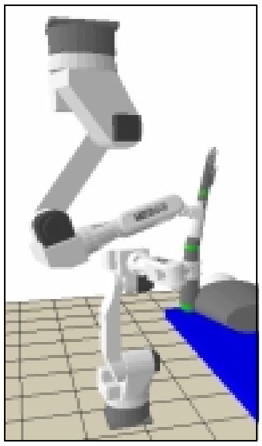
[2] Point is given if simulation proves the easiness of the application.

[3] Including the two robot, controllers and basic software.

[4] Point is given if it is equal to the REHAROB price. If point can’t be given then the manufacturer offering lower price should be preferred.

[5] Treshold is EUR 72000 which was communicated to the pre-selected manufacturers.

[6] ABB offered to cover the IRB 1400 robot to fit medical applications.

Control:						
[1]integration with PC	YES	☑	YES	☑	YES	☑
[1]type of control[7]	position	☒	position	☒	position	☒
[1]access to control gains[8]	YES	☑	YES	☑	NO	☒
Safety:						
[1]EN ISO 10218:1992	YES	☑	YES	☑	YES	☑
[1]93/42/EEC	for RX90 (Ortomaquet)	☑	NO	☒	NO	☒
[1]Simulation support:	YES	☑	YES	☑	YES	☑
						
Subtotal:	12		12		11	
Eligibility:	YES		YES		NO	

(The recently launched RX60LB and IRB 140 robots are not available in IGRIP® yet. A similar robot: A465 of CRS was used in the simulations.)

[7] Point is given if a kind of force control is offered.
[8] Conclusive requirement: quotation is eligible if point is received

Comparison of the robot manufacturers:

Requirement	Stäubli		ABB		Motoman	
[1]manufacturer	Stäubli Robotics World Headquarters (F)	☑	ABB Flexible Automation and Robotics AB (SE)	☑	Motoman Robotics Europe AB (SE)	☑
[1]serial product	YES	☑	YES	☑	YES	☑
[1]product support	many EU countries, not in associated countries	☒	all EU countries, all associated countries	☑	all EU countries, many associated countries	☑
[1]mission	focus on niche market	☑	focus on industry	☒	focus on industry	☒
[1]support to standardisation	YES	☑	YES	☑	YES	☑
[1]subcontractor	FD-Engineering GmbH (A)	☑	ABB AG Flexible Automation Austria (A)	☑	REHM Welding Technology Ltd (HU)	☑
[1]R&D potential	limited support	☒	required support	☑	no support	☒
[1]willingness in the re-negotiations and for the later cooperation with REHAROB (Stäubli and ABB was renegotiated based on the consortium's decision in 5 points: 1. Med. certification 2. Standardization 3. Financial issues 4. Control issues 5. Commitment statement)	- no written commitment for med. certification - no benefit from the med. CE of RX90, - no written commitment for standardisation - rigid payment conditions - no written commitment statement, - delays in communication, - draft offer for services to be subcontraced	☒	- written commitment for standardisation and med. certification, - 10% discount from list price to any REHAROB follow-up sale - deferred payment conditions, - written commitment statement, - good communication and quick reactions, - detailed services to be subcontracted	☑	no re-negotiations happened due to	☒
<u>Subtotal:</u>	5		7		5	
<u>Eligibility:</u>	EC has approved		EC has approved		EC has approved	
<u>Total:</u>	17		19		16	

Based on the evaluation quotation and collaboration offer of ABB was accepted.

7 Specification of the selected ABB robots

Technical data

IRB 140 industrial robot

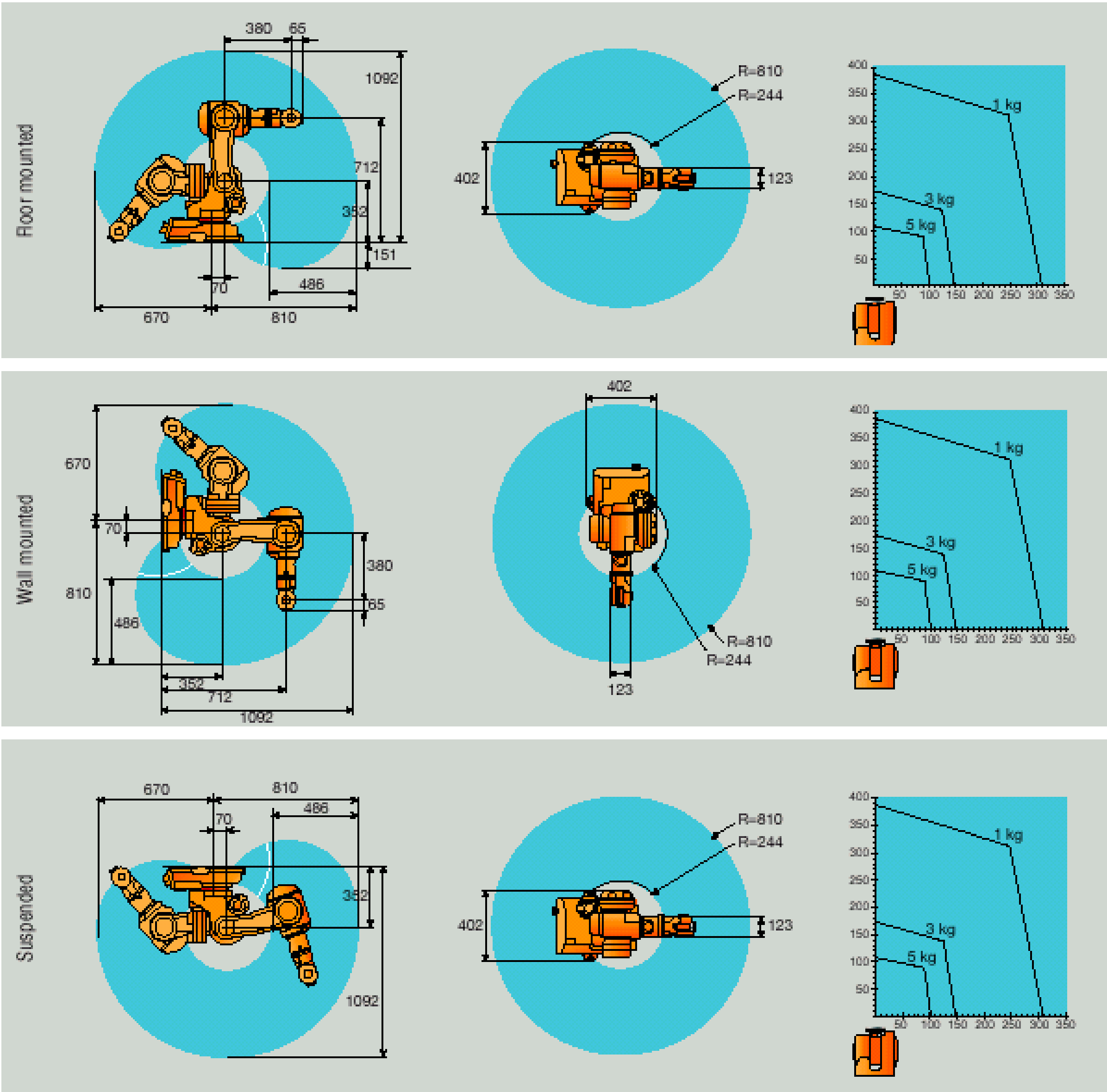
SPECIFICATION			
Robot versions	Handling capacity	Reach of 5th axis	Remarks
IRB 140	5 kg	810 mm	
IRB 140F	5 kg	810 mm	Extra protection
IRB 140CR	5 kg	810 mm	Clean Room

Supplementary load (on upper arm alt. wrist)	
on upper arm	1 kg
on wrist	0.5 kg
Number of axes	
Robot manipulator	6
External devices	6
Integrated signal supply	12 signals on upper arm
Integrated air supply	Max. 8 bar on upper arm
PERFORMANCE	
Position repeatability	±0.03 mm
Axis movement	
Axis	Working range
1, C Rotation	360°
2, B Arm	200°
3, A Arm	280°
4, D Wrist	Unlimited (400° default)
5, E Bend	240°
6, P Turn	Unlimited (800° default)
Movement on ISO test plane, all axes in movement	
Max. TCP velocity	2.5 m/s
Max. TCP acceleration	20 m/s2
Acceleration time 0-1 m/s	0.15 sec.
ELECTRICAL CONNECTIONS	
Supply voltage	200–600 V, 50/60 Hz
Rated power	
Transformer rating	4.5 kVA
PHYSICAL	
Robot mounting	Floor, wall and suspended
Dimensions	
Robot base	400 x 400 mm
Robot controller H x W x D	950 x 800 x 620 mm
Weight	
Robot manipulator	98 kg
Robot controller	250 kg
ENVIRONMENT	
Ambient temperature	
Robot manipulator	5 – 45°C
Robot controller	5 – 52°C
Relative humidity	Max. 95%
Degree of protection, Manipulator	
Standard	IP54
Foundry/Clean Room	IP67
Clean Room	Class 10
Controller	Enclosed air-over Sealed computer, air-over Totally enclosed
Noise level	Max. 70 dB (A)

Safety	Double circuits with supervision, emergency stops and safety functions, 3-position enable device
Emmission	EMC/EMI-shielded
MAN-MACHINE-INTERFACES	
Operators' panel	In cabinet or external
Teach pendant	Portable with joystick and keypad. Display 16 lines x 40 characters. Window style communication. 3 position enabling device, back lighting. 5 user-definable keys, emergency stop.
Languages	Choice of 11 national languages
PC, off-line	"The S4Cplus software on your PC" QuickTeach training on PC RobotStudio™, ProgramMaker™ VirtualRobot simulation
PC, on-line	Monitor and control of robots, FactoryWare™
RRS Simulation	From simulation companies
MACHINE INTERFACES	
Inputs/outputs	Up to 2 x 1 024 signals,
Digital	24 V DC, 120 V AC or relay outputs
Analogue	±10 V and 4-20 mA
Serial channels	Two RS 232 and one RS 422
Networks	2 x Ethernet Allen Bradley PLC
Fieldbus	2 x CAN/Device Net Interbus-S Profibus DP
Process interfaces	Media and signals on upper arm
EXAMPLE OF ARC WELDING EQUIPMENT AND FUNCTIONALITY	
Process equipment	Weld power sources Wire feed systems Welding torches Workpiece manipulators
Example of process signal interface	Status of arc, voltage, current, water, gas, wire feed (digital input) On/off of power, gas, wire feed, error information (digital output) Value of wire feed velocity, voltage, current (analogue output)
Example of ArcWare™ functions	General power source interface Process tuning of welding parameters during program execution (hot edit) Weld-retry including "go-to-service" routine Weld error report and logging Arc start/end Material pre-heating/cooling Scrape start Crater filling Wire burnback Weaving pattern definition Monitoring of arc data, seam coordinates, wire, water, voltage, current, gas
Diskette drive	3.5" MS-DOS
Robot vision	Interface for vision

Data and dimensions may be changed without notice.

Working range and Load diagram



Working range to center of axis 5. All measurements in mm.

Technical data

IRB 1400 industrial robot

SPECIFICATION			
Robot versions	Handling capacity	Reach of 5th axis	Remarks
IRB 1400	5 kg	1.44 m	
IRB 1400H	5 kg	1.28 m	Hanging
Supplementary load			
on axis 3	10 kg		
on axis 1	19 kg		
Number of axes			
Robot manipulator	6		
External devices	6		
Integrated signal supply	12 signals on upper arm		
Integrated air supply	Max. 8 bar on upper arm		

PERFORMANCE		
Positional repeatability	±0.05 mm	
Movements	IRB 1400	IRB 1400H
Max. TCP velocity	2.1 m/s	1.3 m/s
Max. TCP acceleration	15 m/s²	13 m/s²
Acceleration time 0-1 m/s	0.15 sec.	0.15 sec.
Continuous rotation of axis 6		

ELECTRICAL CONNECTIONS	
Supply voltage	200–600 V, 50/60 Hz
Rated power, Transformer rating	4 kVA

PHYSICAL	
Robot mounting	
1400	Floor
1400H	Floor or hanging
Dimensions	
Robot base	620 x 450 mm
Robot controller H x W x D	950 x 800 x 540 mm
Weight	
Robot unit	225 kg
Robot controller	240 kg

ENVIRONMENT	
Ambient temperature	
Robot unit	5 - 45°C
Robot controller	5 - 52°C
Relative humidity	Max. 95%
Degree of protection	Class D (dry) for welding, machining etc.
Noise level	Max. 70 dB (A)
Safety	Double circuits with supervision, emergency stops and safety functions , 3-position enable device
Emmission	EMC/EMI-shielded

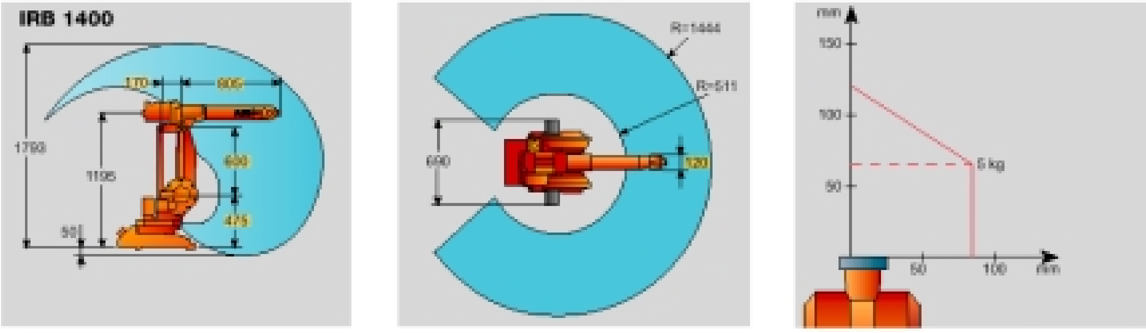
MAN-MACHINE-INTERFACES	
Operators' panel	In cabinet or external
Control pendant	Portable with joystick and keypad. Display 16 lines x 40 characters. Window style communication. 3 position enabling device, back lighting 5 user-definable keys.
Languages	Choice between 10 national languages
Printer	Interface for printer
PC	"The S4C software on your PC"
DeskWare software	QuickTeach training Off-line programming VirtualRobot simulation
FactoryWare software	Monitor and control of robots from PC
RRS Simulation	From simulation companies

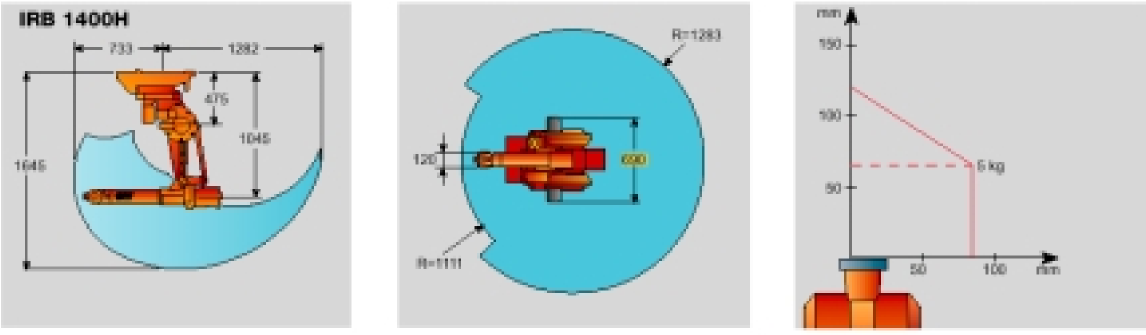
MACHINE INTERFACES	
Digital inputs/outputs	Up to 512, 24 V DC, 120 V AC or relay outputs
Analogue inputs/outputs	Up to 120, ±10 V and ±20 mA
Serial channels	One RS 232 and one RS 485
Network Fieldbus	Ethernet CAN Allen Bradley PLC Interbus-S Profibus
Process Interfaces	Media and signals on upper arm

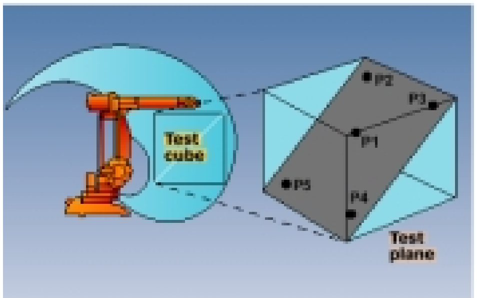
EXAMPLE OF ARC WELDING EQUIPMENT AND FUNCTIONABILITY	
Process equipment	Weld power sources
	Wire feed systems
	Welding torches
	Workpiece manipulators
Examples of process signal interface	Status of arc, voltage, current, water, gas, wire feed (DI)
	On/off of power, gas, wire feed, error information (DO)
	Value of wire feed velocity, voltage, current (AO)
Examples of ArcWare™ functions	General power source interface
	Process tuning of welding parameters during program execution (hot edit)
	Weld-retry, including "go-to-service" routine
	Weld error report and logging
	Arc start/end
	Material pre-heating/cooling
	Scrape start
	Crater filling
	Wire burnback
	Weaving pattern definition
	Monitoring of arc data, seam coordinates wire, water, voltage, current, gas
Diskette drive	3.5" MS-DOS
Robot vision	OptiMaster

Data and dimensions may be changed without notice.

Working Range and load diagram







Average values of tests carried out on the inclined ISO test plane with all robot axes moving.

Examples of ISO test results at rated load and speed

ROBOT TYPE	IRB 1400	IRB 1400H
Rated load	5 kg	5 kg
Rated speed	1 m/s	0.5 m/s
Max. velocity	2.1 m/s	1.3 m/s
Repeatability RP	0.04 mm	0.04 mm
Linear path accuracy AT	1 mm	0.84 mm
Linear path repeatability RT	0.16 mm	0.21 mm
Circular path repeatability RT	0.33 mm	0.21 mm
Minimum positioning time to 0.2 mm		
on 35 mm linear path	0.2 sec	0.3 sec
on 350 mm linear path	0.55 sec	0.6 sec
Average power consumed on ISO test paths	130W	150W

"Rated speed" designates test speed, according to the ISO standards.

Technical data
S4C Industrial Robot Controller

PERFORMANCE	
Controlled axes	12
Control principles	Dynamic model Self optimising Completely coordinated 12 axes interpolation 7-frame coordinate chain Corner path concept Automatic singularity handling
Control hardware	Multi-processor system 32 bit with floating point Up to 24 Mb RAM memory RAM disk Up to 35,000 instructions
Control software	Object-oriented design High-level RAPID robot language Portable, open, expandable PC-DOS file format RobotWare software products
ELECTRICAL CONNECTIONS	
Supply voltage	200-600 V, 50-60 Hz Transformer included
PHYSICAL	
Cabinet size (H x W x D)	950 x 800 x 540 mm same size for complete robot range
Weight	240 kg
Cabinet variants	For process hardware
Lifting eyes	Can be removed
Wheels	Can be mounted
ENVIRONMENT	
Ambient temperature	5-52°C
Relative humidity	max 95%
Form of protection	IP 54
EMC	Immune and emission-free
USER INTERFACES	
Control panel	On cabinet or external
Control pendant	Portable and light Joystick and keypad 5 user-designated keys Display 16 lines x 40 characters Windows-style communication Emergency stop All programming functions available
PC	Connection for PC PC monitoring and control
Off-line	"S4 software on a PC" DeskWare™ software for PC Off-line ProgramMaker™ Virtual robot on PC RRS from simulation companies QuickTeach™ training on PC
Languages	Choice between 10 national languages for MMC and Manuals Possibility to add user dialogues and references
Maintenance	LEDs and test points for electronic boards Diagnostic software Recovery procedures Logging with clock
Safety	Safety and emergency stops Software functions Passwords 2-channel safety circuits with supervision 3-position enable device
MACHINE INTERFACES	
Digital inputs/outputs	up to 512 signals, 24V DC 120V AC or relay outputs
Analogue inputs/outputs	up to 120 signals ±10V ±20 mA
Serial channels	RS 232 and RS 485
Network	Ethernet (10 Mbits per second)
Fieldbuses	Allen Bradley PLC CAN Interbus-S Profibus
Process interfaces	Media and signals for upper arm Space in controller for equipment
Robot vision	OptiMaster integrated
Diskette drive	For 3.5" MS-DOS
SENSOR INTERFACES	
Search stop with automatic program shift	
Vision system	
Seam tracking	
Contour tracking	
Conveyor following	
USER DEFINED FUNCTIONALITY	
Program instructions Operator dialogues Names for all objects and data I/O and instruction pick lists Predefined data Robot configuration Start-up sequences Corner paths Process monitoring Event logging Diagnostics, error messages Error handling	
PROGRAM FEATURES	
Pull-down menus, dialogues and joystick for robot motion, function keys and windows Cut-and-paste, copy, delete, search, change functions, undo Manager functions for different user needs File handling RAPID – powerful and open robot language ProcessWare, application software packages Motion to a position or fly-by at a defined distance Linear, joint and circular interpolation Mirror function Soft servo function Unlimited rotating axes 4 and 6 Restart on path Forward/backward/simulated wait and input testing Multi-tasking functions Concurrent I/O function Independant motion of external axes Position fixed I/O function Master-slave functions Real time clock function Hot-edit functions Unlimited number of data	

Data and dimensions may be changed without notice.

ABB

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EN 50082-2	EN 50082-2 EMC, Generic immunity standard
EN 55011	EN 55011 Class A
EN 563	EN 563 Safety of machinery, temperature of surfaces
EN 60204	EN 60204 Electrical equipment for industrial machines
EN 61000-4-2	EN 61000-4-2 Electrostatic discharge immunity test
EN 61000-4-3	EN 61000-4-3 Radiated, radio-frequency. Electromagnetic field immunity test
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