Work Life in the Light of the Demographic Change: Case Study Force Assistive Device for Craftsmen

Steffen Petereit[1], Amos Albert[1], Nidhal Jeridi[2], Richard Schoenleber[1], Christof Rebmann[1], and Heike Vallery[2]

[1] Robert Bosch GmbH, Central Research and Advance Engineering, 71701 Schwieberdingen, Germany
[2] ETH Zurich, Institute of Robotics and Intelligent Systems, Sensory–Motor Systems Lab, CH–8092 Zurich, Switzerland

Abstract. The trend of aging society has impacts on all parts of daily life. For instance work lifetime is expected to increase and in combination with rising quality and efficiency demands there is need for new technologies, working processes and assistance systems. For the latter, applied to the domain of craftsmen, systems seem to be reasonable which allow force assistance, augmentation, increase in safety and/or guidance functions. Required technology blocks to implement such functions are mainly available already today. This article is dealing with force assistance and describes an electro–mechanical system – the demonstrator of a so called "3rd Arm" – which actively supports the user when handling heavy power tools. The "3rd Arm" consists mainly of cost–effective mass–market compliant components. It is attached to a harness at the waist of the craftsman and relieves craftsmen from hard and fatiguing works. Two functions were implemented and evaluated. First the compensation of gravitational forces of the tool by means of a force control in order to achieve an utmost transparent behaviour. Secondly, so called "Virtual Fixtures" were used to implement a positioning assistance when repeating tasks are to be fulfilled at the same working height.

1 Motivation

In many areas of daily life (household, work and leisure time) a trend towards increased use of assistance functions and autonomous systems can be observed. "Aging society" is one of the key drivers whereas the increased availability of the necessary technologies serves as an enabler. In work life "aging society" is reflected in a constantly prolonging work life with at the same time increasing demands of quality and efficiency. However, with increasing age the physical fitness is declining. To compensate for this reduction of physical fitness, assistance systems can be used, such as so called "Wearable Robots". These are portable robot systems which can assist, improve or even replace the function of human extremities (see e.g. [1] for an overview). A distinction is made between therapeutical exoskeletons, robotic exoprostheses and extender–exoskeletons which multiply the muscular force. The latter can either run parallel to the user's extremities or can be formed as an end effector system which is only connected to the user at the end points (usually the hands). The system compensates respectively transfers forces which would otherwise act directly on the human body and introduces them at a less sensitive point at the torso or directs then to the ground. The use of robotic assistance systems in work environment can reduce the physical load, especially on the upper body. This prevents orthopedic long–term damage and enables a longer worklife while at the same time enhancing work efficiency and quality, even when performing heavy physical work. In production environment and in logistics applications actuated force– and lifting–assistance is already in use (e.g. available from Dalmec Ltd., UK or Scaglia INDEVA Spa, Italy). All known systems are stationary (not portable) and they require in part infrastructural changes. Other systems to support upper body regions can be found in the domain of rehabilitation, which are mostly stationary as well (for examples see [2,3,4,5]). Portable therapeutical systems are limited to specialized control functions, e.g. in the assistance to tremor patients [6]. Portable systems are also known from military and fundamental research, such as XOS (Raytheon/Sarcos Company, USA), BLEEX [7] (only for lower extremities) or HAL [8], which all address force assistance.

This paper introduces a system called "3rd Arm" which relieves craftsmen when working with heavy machine hand tools.

In order to evaluate how close such a system may be to commercialization in mass markets we considered as prerequisite the use of off–the–shelf low cost components.

For illustration purposes a typical use case is shown in Fig. 1. For mounting of insulation panels on the outside walls of buildings many drill holes have to be positioned in a regular pattern. The drilling machines used are rather heavy and the work is fatiguing. The use of floor–based support systems on construction sites is very restricted if not impossible (due to scaffolding). Therefore a portable, body mounted system is suggested.

The paper is structured as follows: Section 2 first describes the electromechanical system which was designed considering ergonomic aspects. Furthermore the sensor system, the electronic circuits and the safety system are described.

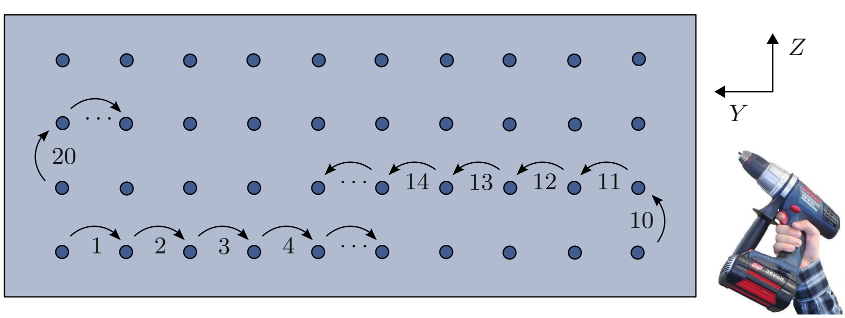

Fig. 1. Drill hole pattern for application of outside wall insulation

Section 3 describes the design of the controller structure, including the steps of modelling, system identification and application as well as the implemented control and assistance functions. Qualitative evaluation results of a small (not representative) study can be found in Sect. 4. The article closes with a summary and a short outlook.

2 Electromechanical System of "3rd Arm"

Unlike in classical exoskeleton systems the "3rd Arm" does not run in parallel to the users arm. Also it is not the users hand or forearm which is supported. Instead, it is the heavy working tool itself that is mounted on the actuated support structure of the "3rd Arm", which in return is then mounted on a harness worn by the user. Sensors on the control handle detect the users operating forces (user desire) which are then amplified by the actuators. The system is designed as an underactuated system for weight compensation and height positioning assistance.

2.1 Mechanical Setup

To ensure an invariable parallel orientation of the working tool the main system structure is carried out as a parallelogram structure (Fig. 2). The system's actuation is implemented by diagonally arranged linear drives. Tension springs are used to minimize the energy required to hold the static system (gravity compensation). This way the drives only need to deflect the system from a balanced middle position (Fig. 3). The linear actuators consist of low–cost brushed DC motors with 5 : 1 planetary gears which drive ball screw spindles.

As shown in Fig. 4 the system itself is mounted on a harness on the user's back and waist.

One requirement for the layout of the kinematic structure was that force–assisted working is possible within the entire human work space (Fig. 5). It shall be ensured that the system is usable within this workspace without any deadlocks (= singularities).

2.2 Electronic System

Designing the system as a "wearable robot" provokes the following constraints:

- highest possible safety requirements due to high degree of interaction between man and machine
- high energy efficiency (energy storage has to be carried by user): low dissipation loss, high degree of efficiency for all components
- robustness due to targeted application area (craftsmen, construction sites)

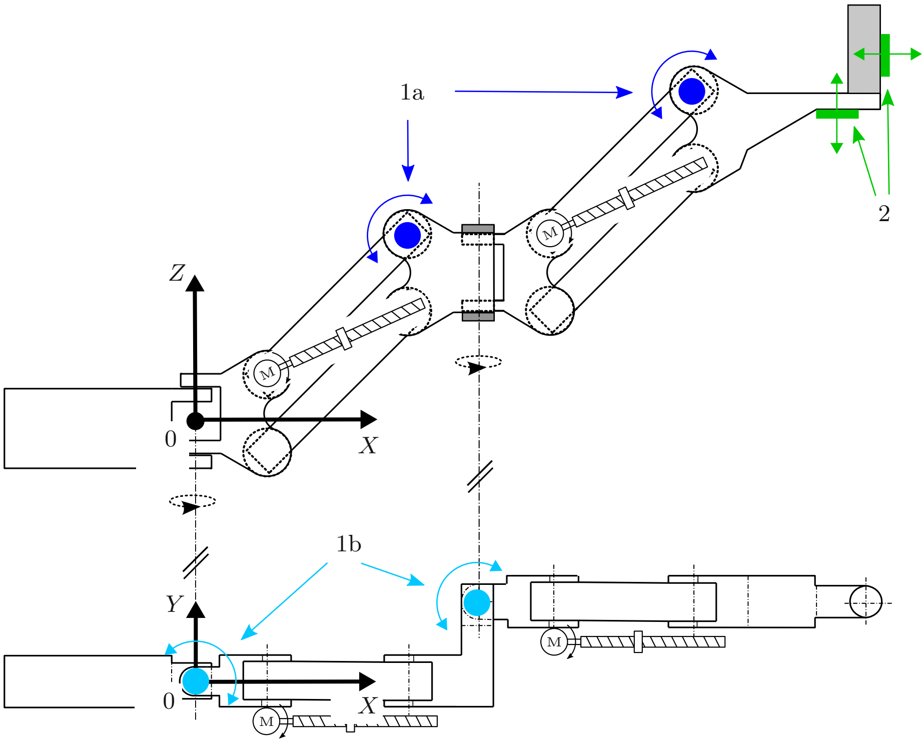

Fig. 2. Mechanical setup as parallelogram structure with $f = 4$ Degrees of Freedom (DoF): two active DoF in z–direction and two passive DoF rotating around z–axis. (1) angle sensors, (2) force sensors.

Microcontroller. Two microcontrollers are used to control the system:

- μC1 (ARM9 Core, 32–bit, 266 MHz), which represents the outer control loop of the cascaded control (force control) and which is also responsible for data processing of the higher software layers
- μC2 (MPC560xP, 32–bit, 64 MHz) for interfacing sensors and actuators also implements the inner control loops (e.g. motor current control) and implements as well the relevant monitoring functions (e.g. overcurrent protection, battery charge state)

Safety Circuits. Both microcontrollers continuously generate a pulse width modulation signal (alive–signal) which is monitored by a discrete safety circuit. As soon as the signal parameters show signs of irregularity the system is switched in hardware to a fail–safe mode. The maximum allowed angles of the joints are monitored by software as well as by hardware limit switches which are directly wired to relays and switch off the drives immediately in case of contact.

Fig. 3. Linear actuator with tension springs

Fig. 4. Assistive support system “3rd Arm”

Sensor System. For the implementation of the basic functions the joint positions of the active joints as well as the user desire have to be detected. The joint positions can either be measured directly at the joint pivot point or derived indirectly by the position of the drive spindle of the actuator. To minimize interference of elasticities of the mechanical system a joint position measurement directly at the joint pivot point was considered. This is done contactless by a magnetic angle encoder with 10– or 12–bit resolution. The user request detection is done by force measurement on the handle. To ensure a high transparency of the system even smallest changes in hand forces applied by the user have to be detected. The system as described here uses strain gauges which like the magnetic angle decoders are free of wear.

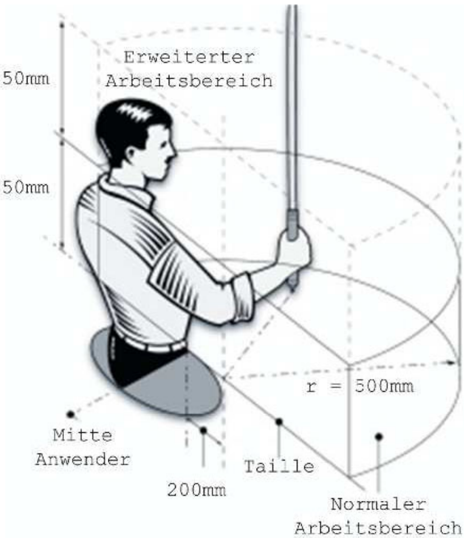

Fig. 5. The human workspace [9]

3 Control

The following steps were carried out for control design:

- modelling and simulation
- system parameter identification
- selection of suitable control structures
- implementation of additional functions

The following subsections describe these steps in detail.

3.1 Modelling

Modelling was done by means of a multibody system. The system was cut free at the user anchor point which eliminates the user's body movements (Fig. 6). As a result the vector of generalized variables is of 4^{th} degree

$$\boldsymbol{q}(t) = \left[\ \underbrace{q_1(t)\ q_2(t)\ q_3(t)\ q_4(t)}_{\text{Robot}}\ \underbrace{\cancel{X_0\ Y_0\ Z_0\ \theta_1\ \theta_2\ \theta_3}}_{\text{User}}\ \right] \tag{1}$$

with the particular variables described in Fig. 6.

Figure 7 depicts the respective mechanical components like masses and lengths. The masses are assumed as concentrated. From this model the forward kinematics for the end effector position $\boldsymbol{P}_{\text{Effector}}(t)$ can be determined

$$\boldsymbol{P}_{\text{Effector}}(t) = \boldsymbol{\varphi}\big(\boldsymbol{q}(t)\big), \quad \boldsymbol{\varphi}(\cdot) : \mathrm{I\!R}^4 \to \mathrm{I\!R}^3 \tag{2}$$

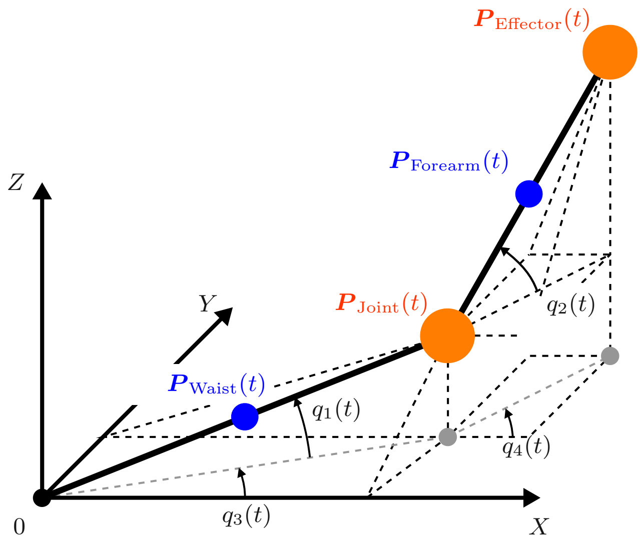

Fig. 6. Simplified system neglecting user's body movement

The partial derivative with respect to the generalized coordinates $\boldsymbol{q}(t)$ delivers the Jacobi–Matrix $\boldsymbol{J}(\boldsymbol{q})$

$$\boldsymbol{J}(\boldsymbol{q}) = \frac{\partial \boldsymbol{\varphi}\big(\boldsymbol{q}(t)\big)}{\partial \boldsymbol{q}(t)} \tag{3}$$

Using the kinetic and potential energy of the overall system ($T(t)$ and $U(t)$) the Lagrange function $L(t)$ can be set up. Using the Lagrange equations

$$\frac{d}{dt}\left(\frac{\partial L(t)}{\partial \dot{\boldsymbol{q}}(t)}\right) - \frac{\partial L(t)}{\partial \boldsymbol{q}(t)} = \boldsymbol{\tau}_{\text{Ext}}(t), \quad L(t) = T(t) - U(t) \tag{4}$$

the descriptive differential equations of motion can be derived as follows.

$$\boldsymbol{M}\big(\boldsymbol{q}(t)\big)\,\ddot{\boldsymbol{q}}(t) + \boldsymbol{C}\big(\boldsymbol{q}(t), \dot{\boldsymbol{q}}(t)\big) + \boldsymbol{F}\big(\boldsymbol{q}(t), \dot{\boldsymbol{q}}(t)\big) + \boldsymbol{G}\big(\boldsymbol{q}(t)\big) + \boldsymbol{\tau}_{\text{Elas}}(t) = \boldsymbol{\tau}_{\text{Ext}}(t) \tag{5}$$

In known notation $\boldsymbol{M}\big(\boldsymbol{q}(t)\big)$ represents the mass matrix which describes inertial effects, the vector $\boldsymbol{C}\big(\boldsymbol{q}(t), \dot{\boldsymbol{q}}(t)\big)$ describes the Coriolis– and centrifugal terms, $\boldsymbol{F}\big(\boldsymbol{q}(t), \dot{\boldsymbol{q}}(t)\big)$ is the vector of the friction effects, $\boldsymbol{G}\big(\boldsymbol{q}(t)\big)$ is the vector of the gravitational terms, $\boldsymbol{\tau}_{\text{Elas}}(t)$ represents the elastic terms and $\boldsymbol{\tau}_{\text{Ext}}(t)$ represents the vector of the generalized external forces and torques.

Using the Jacobi–Matrix $\boldsymbol{J}(\boldsymbol{q})$ the projected workspace was analyzed for singularities. By choosing suitable parameters for the mechanical system (limb lengths and permissible joint angles) it is ensured that no singularities (= deadlocks) can occur within the chosen workspace. Figure 8 visualizes the geometrical location of singularities, which are all located outside the reachable workspace.

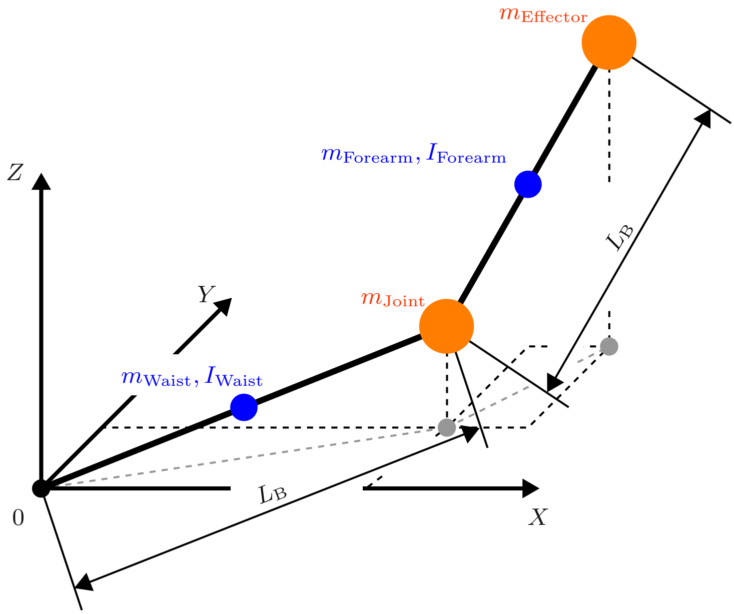

Fig. 7. Kinematic structure of the simplified model with masses and lengths

3.2 Parameter Identification

For identification of the unknown system parameters only the active joints were considered, i.e. the passive pivoting motions in the horizontal plane (along z–axis) were neglected. By use of suitable excitation, gravitational parameters, actuator inertia and dry and viscous friction parameters were successively determined. For doing so the equations of motion were reformulated in a way that they could be described using a linear parameter vector $\boldsymbol{\Lambda}$ of minimal order and a system matrix $\boldsymbol{W}$ that describes all nonlinear terms of the model (base parameter method):

$$\boldsymbol{\tau}_{\text{Ext}}(t)-\boldsymbol{\tau}_{\text{Elas}}(t) = \boldsymbol{M}\big(\boldsymbol{q}(t)\big)\ddot{\boldsymbol{q}}(t)+\boldsymbol{C}\big(\boldsymbol{q}(t),\dot{\boldsymbol{q}}(t)\big)+\boldsymbol{F}\big(\boldsymbol{q}(t),\dot{\boldsymbol{q}}(t)\big)+\boldsymbol{G}\big(\boldsymbol{q}(t)\big) \quad (6)$$

$$\Delta\boldsymbol{\tau}(t) = \boldsymbol{W}\big(\boldsymbol{q}(t),\dot{\boldsymbol{q}}(t),\ddot{\boldsymbol{q}}(t)\big)\ \boldsymbol{\Lambda} \quad (7)$$

This was followed by a two–stage identification, for which a partitioning of the linear parameter vector $\boldsymbol{\Lambda}$ in two vectors $\boldsymbol{\lambda}_{\text{G}}$, $\boldsymbol{\lambda}_{\text{I}}$ and the system matrix $\boldsymbol{W}(\cdot)$ in three matrixes $\boldsymbol{W}_1(\cdot)$, $\boldsymbol{W}_2(\cdot)$, $\boldsymbol{W}_3(\cdot)$ was carried out:

$$\Delta\boldsymbol{\tau}(t) = \boldsymbol{W}_1\big(\boldsymbol{q}(t),\dot{\boldsymbol{q}}(t)\big)\ \boldsymbol{\lambda}_{\text{G}} + \boldsymbol{W}_2\big(\boldsymbol{q}(t),\ddot{\boldsymbol{q}}(t)\big)\ \boldsymbol{\lambda}_{\text{G}} + \boldsymbol{W}_3\big(\dot{\boldsymbol{q}}(t),\ddot{\boldsymbol{q}}(t)\big)\ \boldsymbol{\lambda}_{\text{I}} \quad (8)$$

Finally a parameter estimation using the Least–Squares method was done. For determining the gravitational parameters the system was excitated with

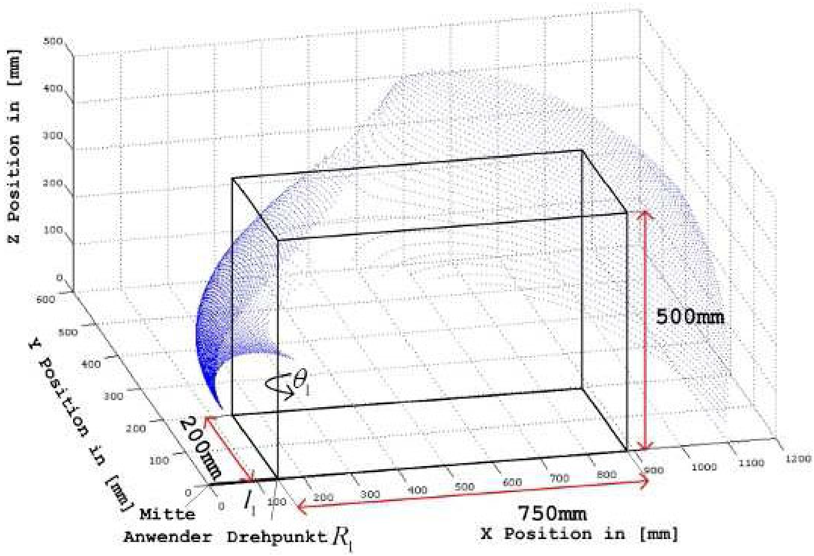

Fig. 8. Point cloud with singularities of the end effector (blue dots). Compared with chosen workspace (box), which is free of singularities.

trapezoidal trajectories with a low angular velocity (quasi–stationary). By doing so all system elements associated with acceleration are eliminated

$$\Delta\boldsymbol{\tau}(t) = \boldsymbol{W}_1(\cdot)\ \boldsymbol{\lambda}_{\mathrm{G}} \tag{9}$$

From that the gravitational and dry friction parameters can be determined as

$$\boldsymbol{\lambda}_{\mathrm{G}} = \left(\boldsymbol{W}_1(\cdot)^{\mathrm{T}}\ \boldsymbol{W}_1(\cdot)\right)^{-1} \boldsymbol{W}_1(\cdot)^{\mathrm{T}}\ \Delta\boldsymbol{\tau}(t) \tag{10}$$

In a second step an excitation with a higher share of acceleration was applied. Making use of the already estimated parameters leads to

$$\underbrace{\Delta\boldsymbol{\tau}(t) - \boldsymbol{W}_1(\cdot)\ \boldsymbol{\lambda}_{\mathrm{G}} - \boldsymbol{W}_2(\cdot)\ \boldsymbol{\lambda}_{\mathrm{G}}}_{\Delta\boldsymbol{\tau}'(t)} = \boldsymbol{W}_3(\cdot)\ \boldsymbol{\lambda}_{\mathrm{I}} \tag{11}$$

The rest of the parameters (inertial and viscous friction parameters) are then calculated as follows:

$$\boldsymbol{\lambda}_{\mathrm{I}} = \left(\boldsymbol{W}_3(\cdot)^{\mathrm{T}}\ \boldsymbol{W}_3(\cdot)\right)^{-1} \boldsymbol{W}_3(\cdot)^{\mathrm{T}}\ \Delta\boldsymbol{\tau}'(t) \tag{12}$$

A comparison between measurements done on the actual system and a simulation using the estimated parameters shows a good correlation (see Fig. 9).

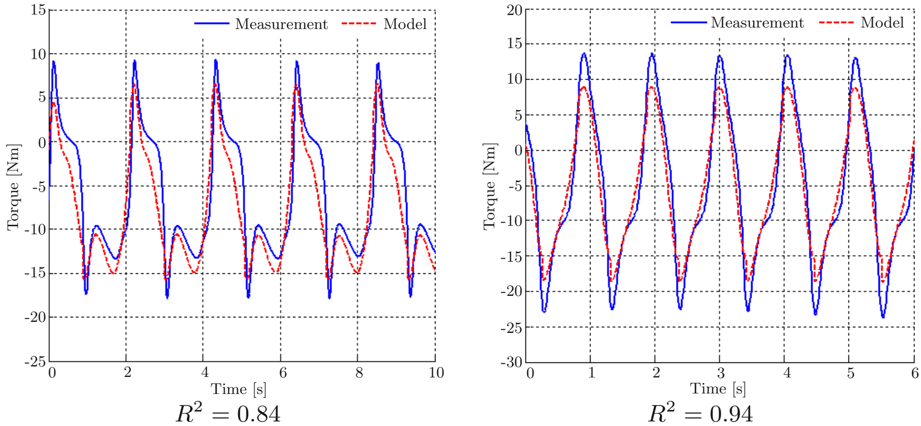

Fig. 9. Comparison of measurement data and simulation result regarding torque for identical movements. The coefficient of determination R^2 indicates a good correlation.

3.3 Control Strategy

A vital prerequisite for the acceptance is a suitable design of the man machine interface. For that reason the control design is of high importance, e.g. in order to obtain a high degree of system transparency. Several control principles are known and are the subject of intensive research. Haptic interfaces are typically based on impedance or admittance control [10]. Such approaches allow for compensation of the manipulator's weight and to some extend also of its inertia. "Generalized Elasticities" [11] can be used to mask remaining inertias from the user. To assist the user in performing special tasks such as telepresence operations "Virtual Fixtures" [12] are used, which limit the user's movements to certain areas or directions. When using the hierarchical concept of "Shared Control" [13,14,15], the user's task is mainly motion planning, while the fine manipulation is done by subordinate control loops. Robotic support can also be realized elastic, e.g. using potential fields which indicate correct movements without enforcing them. For actuated prosthestic legs or exoskeletons the method of "Complementary Limb Motion Estimation" [16,17] is known, which uses the motion pattern of the rest of the body to estimate the desired motion of the supported limb. A pure force assistance system such as BLEEX [18] can increase physical performance. Prerequisite for the use of the control principles "Generalized Elasticities" und "Shared Control" is that the movement patterns are known in advance. The use of "Complementary Limb Motion Estimation" is only practical if the movement of the limbs can be measured. Therefore, for an assistive system for craftsmen which should allow most flexible operation especially the principle of impedance control for gravity compensation in combination with "Virtual Fixtures" for providing potential fields seems to be promising.

Zero–Force Control. The following is valid for the zero–force control in this system:

– passive actuation of the assistance system by external forces
– forces acting on the end effector have to be compensated by torques applied to the joints

The principle of "virtual work" is used to derive the interrelation of external forces and actuator torques. The interrelation results from the already introduced Jacobi–Matrix:

$$\boldsymbol{\tau}(t) = \boldsymbol{J}(\boldsymbol{q})^{\mathrm{T}}\ \boldsymbol{F}(t) \tag{13}$$

$$\begin{bmatrix} \tau_1(t) \\ \tau_2(t) \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} -L_{\mathrm{B}}\ s_1\ c_3 & -L_{\mathrm{B}}\ s_1\ s_3 & L_{\mathrm{B}}\ c_1 \\ -L_{\mathrm{B}}\ s_2\ c_{3+4} & -L_{\mathrm{B}}\ s_2\ s_{3+4} & L_{\mathrm{B}}\ c_2 \\ -L_{\mathrm{B}}\,(c_1 s_3 + c_2 s_{3+4}) & -L_{\mathrm{B}}\,(c_1 c_3 + c_2 c_{3+4}) & 0 \\ L_{\mathrm{B}}\ c_2\ s_{3+4} & L_{\mathrm{B}}\ c_2\ c_{3+4} & 0 \end{bmatrix} \begin{bmatrix} F_{\mathrm{x}}(t) \\ F_{\mathrm{y}}(t) \\ F_{\mathrm{z}}(t) \end{bmatrix} \tag{14}$$

whereas s_1 is a short notation for $\sin\big(q_1(t)\big)$ and s_{3+4} for $\sin\big(q_3(t) + q_4(t)\big)$ (respectively c_1 and so on).

An actuation is only possible in z–direction, in x– and y–direction the system is passive. Hence the following applies:

$$F_{\mathrm{x}}(t) = F_{\mathrm{y}}(t) = 0 \tag{15}$$

The distribution of the z–force on both actuators is determined as

$$\begin{bmatrix} \tau_1(t) \\ \tau_2(t) \end{bmatrix} = \begin{bmatrix} L_{\mathrm{B}}\ c_1 \\ L_{\mathrm{B}}\ c_2 \end{bmatrix} F_{\mathrm{z}}(t) \tag{16}$$

Impedance Control in Cartesian Space. Figure 10 shows the implemented controller structure which consists of four elements. The inner loop implements a force control loop (1). Feed–forward elements compensate gravitational terms of the tool weight and the weight of the "3$^{\mathrm{rd}}$ Arm" itself (2). A safety function ensures that the system stiffens in the proximity of the end stops, i.e. the actuators produce an increasing counterforce as the end stops are approached (3). Finally, the guidance function is implemented in an outer control loop by generating force setpoints (4). That way the system can e.g. be stiffened at predefined height levels ("Virtual Fixtures").

Additional Functions. In addition to the gravity compensation of the working tool, additional assistive functions may offer benefit for the user.

Additional Function Positioning Aid. The use case shown in Fig. 1 requires for many drill holes set at identical height levels. The user is supported by a virtual "lock" of the working tool at a height. When the user approaches with the tool the height of the target plane, the tool is "attracted" in z–direction, i.e. it slips on a virtual potential plane to its target height. To leave this potential plane in z–direction up– or downwards, a force has to be applied. The movement between the potential planes is then effortless again, i.e. the zero–force control is applied (see Fig. 11, 12).

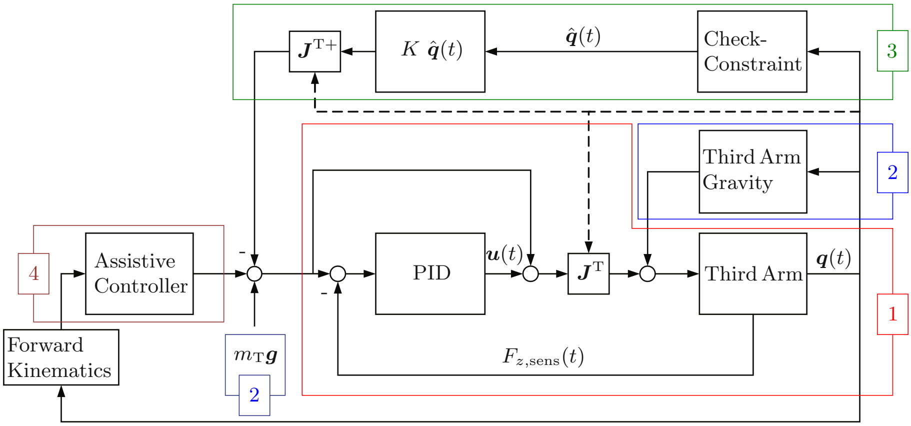

Fig. 10. Complete controller structure including force control loop (1), feed–forward of gravitational terms (2), system stiffening in proximity to end stops (3), potential field based assistance function (4)

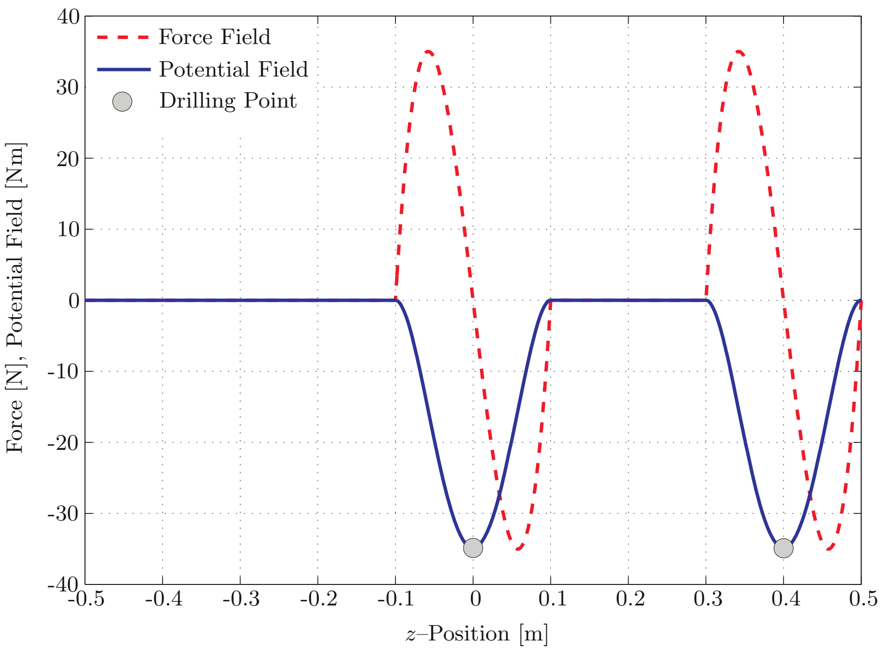

Fig. 11. Positioning aid using a potential function: In this example z–position locks are set at $z = 0\,\text{m}$ and $z = 0.4\,\text{m}$

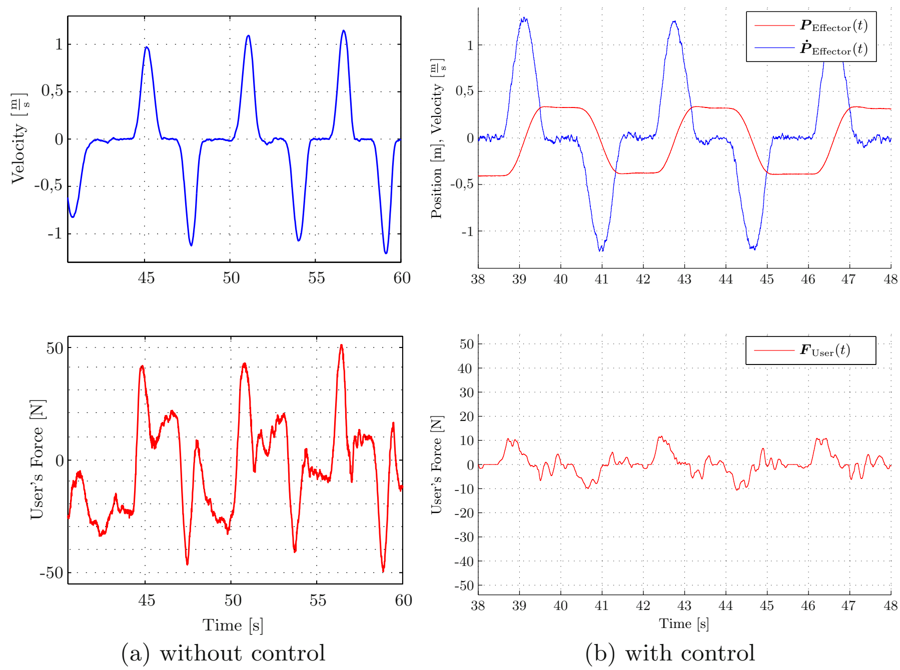

Fig. 12. User's force required without (a) and with force assistance system (b) at comparable speed profiles

Compensation of User's Body Movements. Up to now the user's body movements have been neglected in the control structure. Yet these are omnipresent (due to walking, breathing, uneven ground, etc.) and influence the absolute positioning of the end effector in the workspace. As long as these movements are known they can be compensated and balanced out. For detecting the user's body movements e.g. laser scanners can be used which determine the systems position in space. A cost–effective approach is the use of laser range finders e.g. on the end effector which measure the three spatial directions. As long as the system is only actuated in z–direction (as described here) the use of one laser range finder in z–direction is sufficient. This system extension still needs to be implemented.

4 Evaluation

4.1 System Evaluation

The comparison of a passive to our active support system shows a significant reduction of the users actuation force (Fig. 12).

Also the implemented z–positioning assistance using potential planes showed good results (Fig. 13).

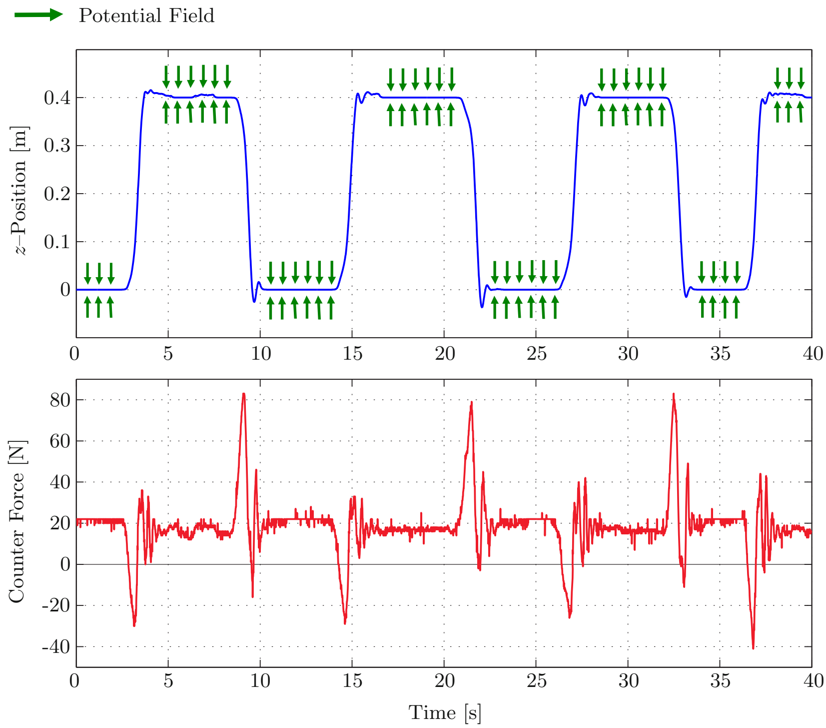

Fig. 13. z–positioning assistance using potential functions: Counter forces applied by system to ensure attraction to desired height plane.

4.2 Derived Success Factors

The force applied by the user is a measurable parameter to indicate the functional quality. Yet for the evaluation of haptic man–machine–interactions it is advisable to take into account subjective criteria (feel and touch) as well in addition to the purely objective criteria. For doing so a small user survey was conducted (ten test persons). Evaluated was the overall functionality, the necessary user force (transparency), manoeuvrability and different z–position potential functions. The overall functionality was rated positive. The necessary force was reduced by over 75 %.

The acceptance tests also showed the following success factors:

– high degree of transparency necessary (to compensate for the elasticities of the mechanical system)
– low system weight, especially of the "3rd Arm" itself
– low power consumption (as far as possible assisted by springs)
– sufficient robustness for projected work environment "craftsmen/construction site"

5 Summary and Outlook

A first demonstrator of a "3rd Arm" support device has been set up, which offers assistance when working with heavy machine tools. Two functions are implemented and tested: Force assistance for gravity compensation and a positioning aid function for repetitive working tasks in defined working heights. In a short survey success factors were derived which will be considered in the development of the next version. On the one hand this is a weight reduction (due to a transfer of the actuators from the "3rd Arm" to the harness), on the other hand an increase of the systems transparency due to a control system with higher bandwidth. In addition to that the system will be extended by a localization system to enable additional functions.

References

1. Pons, J.L., et al.: Wearable Robots – Biomechatronic Exosceletons. John Wiley & Sons (2008)
2. Hogan, N., Krebs, H., Sharon, A., Chamnarong, J.: Interactive Robotic Therapist. US patent 5, 466, 213 (1995)
3. Casadio, M., Sanguineti, V., Morasso, P.G., Arrichiello, V.: Braccio di Ferro: A New Haptic Workstation for Neuromotor Rehabilitation. Technology and Health Care 14, 123–142 (2006)
4. Nef, T., Mihelj, M., Riener, R.: ARMin: A Robot for Patient–Cooperative Arm Therapy. Medical & Biological Engineering & Computing 45(9), 887–900 (2007)
5. Stienen, A., Hekman, E., Van der Helm, F., Prange, G., Jannink, M., Aalsma, A., Van der Kooij, H.: Dampace: Dynamic Force–Coordination Trainer for the Upper Extremities. In: Proc. of IEEE Int. Conf. on Rehabilitation Robotics (ICORR), pp. 820–826 (2007)
6. Rocon, E., Belda–Lois, J., Ruiz, A., Manto, M., Moreno, J., Pons, J.: Design and Validation of a Rehabilitation Robotic Exoskeleton for Tremor Assessment and Suppression. IEEE Transact. on Neural Systems and Rehabilitation Eng. 15, 367–378 (2007)
7. Chu, A., Kazerooni, H., Zoss, A.: On the Biomimetic Design of the Berkeley Lower Extremity Exoskeleton (BLEEX). In: Proc. of IEEE International Conference on Robotics and Automation, pp. 4356–4363 (2005)
8. Kawamoto, H., Kanbe, S.: Power Assist Method for HAL3 – Estimating Operator Intention Based on Motion Information. In: Proc. of IEEE International Workshop on Robot and Human Interactive Communication, pp. 67–72 (2003)
9. Desoutter: Ergosense – Ergonomie am Arbeitsplatz (May 2003), http://www.klasand.si/docs/CP_Ergo-nomie_am_Arbeitsplatz_deu.pdf
10. Hogan, N.: Impedance Control: An Approach to Manipulation. Part I – Theory, Part II – Implementation, Part III – Applications. ASME Journal of Dynamic Systems, Measurement and Control 107, 1–24 (1985)
11. Vallery, H., Duschau–Wicke, A., Riener, R.: Generalized Elasticities Improve Patient–Cooperative Control of Rehabilitation Robots. In: Proc. of IEEE International Conference on Rehabilitation Robotics, pp. 535–541 (2009)
12. Rosenberg, L.B.: Virtual Fixtures: Perceptual Tools for Telerobotic Manipulation. In: Proc. of IEEE Annual Int. Symposium on Virtual Reality (1993)

13. Griffin, W.B.: Shared Control for Dexterous Telemanipulation with Haptic Feedback. Ph.D. Thesis Dept of Mechanical Engineering Stanford University (2003)
14. Aarno, D.: Intention Recognition in Human Machine Collaborative Systems. Ph.D. Thesis KTH School of Computer Science and Communication (2007)
15. Unterhinninghofen, U., Freyberger, F.K.B., Buss, M.: Study on Computer Assistance for Telepresent Reaching Movements. In: Ferre, M. (ed.) EuroHaptics 2008. LNCS, vol. 5024, pp. 745–754. Springer, Heidelberg (2008)
16. Vallery, H., Van Asseldonk, E., Buss, M., Van der Kooij, H.: Reference Trajectory Generation for Rehabilitation Robots: Complementary Limb Motion Estimation. IEEE Transactions on Neural Systems and Rehabilitation Engineering 17, 23–30 (2009)
17. Vallery, H., Burgkart, R., Hartmann, C., Mitternacht, J., Riener, R., Buss, M.: Complementary Limb Motion Estimation for the Control of Active Knee Prostheses. In: Proc. of European Conf. on Technically Assisted Rehabilitation, vol. 56, pp. 45–51 (2011)
18. Kazerooni, H., Racine, J.L., Huang, L., Steger, R.: On the Control of the Berkeley Lower Extremity Exoskeleton (BLEEX). In: Proc. of IEEE Int. Conference on Robotics and Automation (2005)