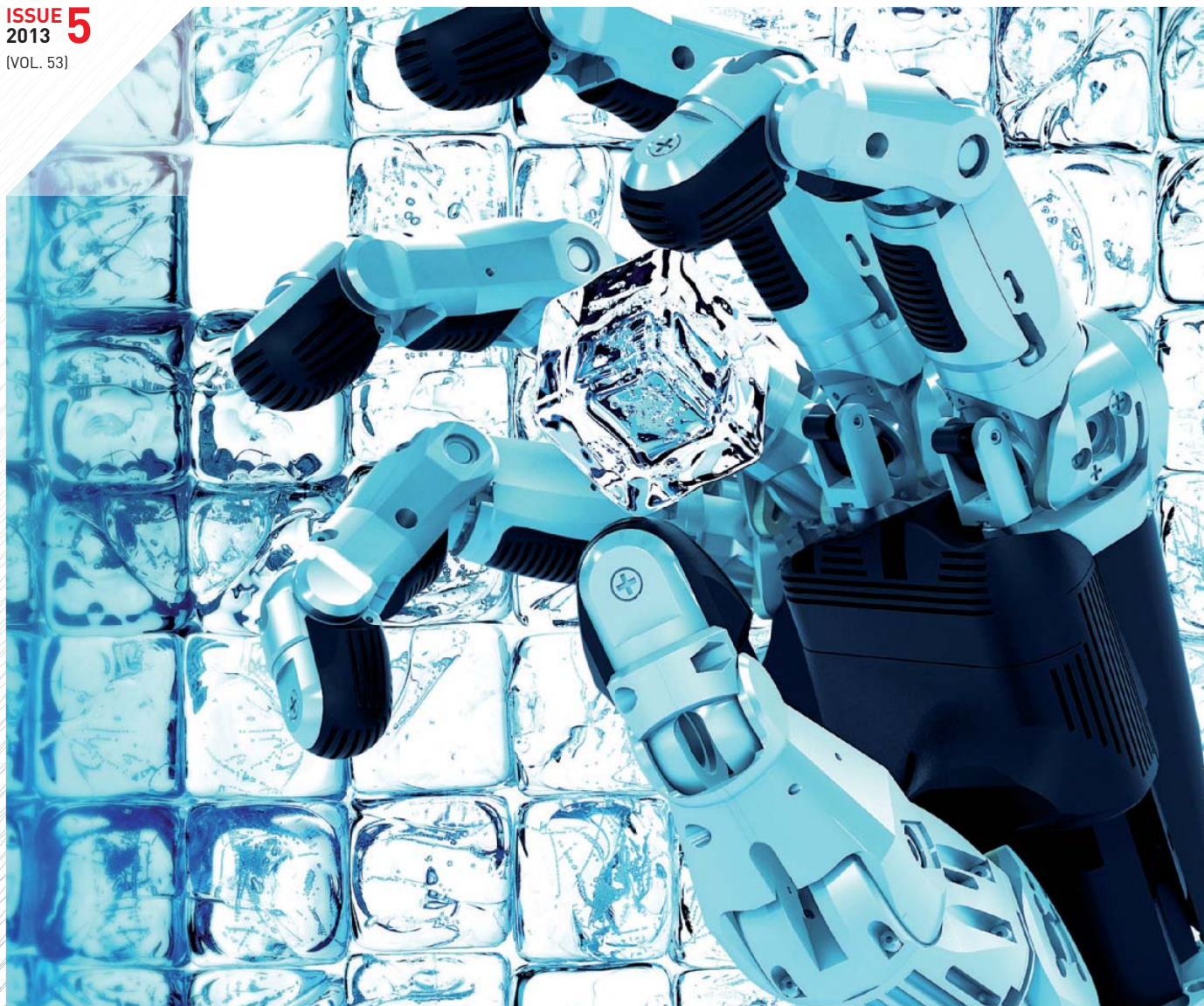


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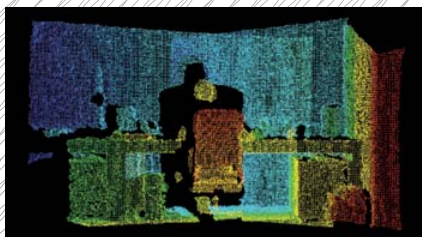
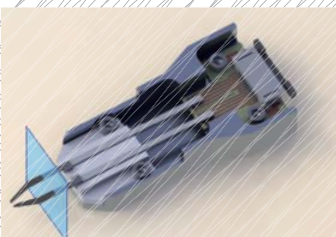
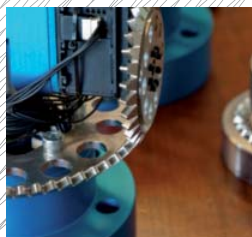
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SPECIAL ISSUE: **ROBOTICS – DESIGN, CONTROL AND APPLICATIONS**

■ ALGORITHMS ■ CONSTRUCTION ■ TELE-OPERATION ■ COBOTICS

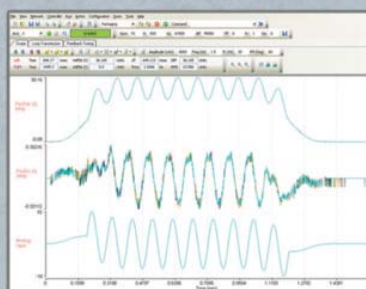


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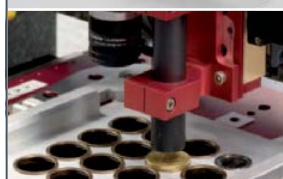
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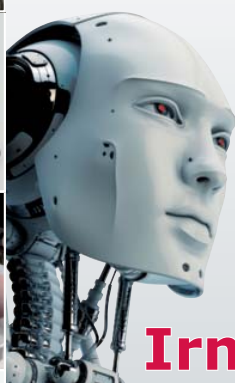
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The main cover photo (5-finger hand) is courtesy of Schunk.

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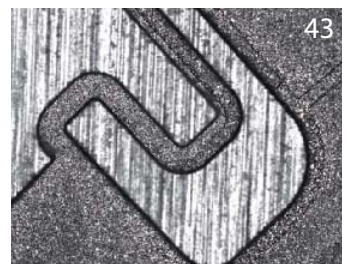
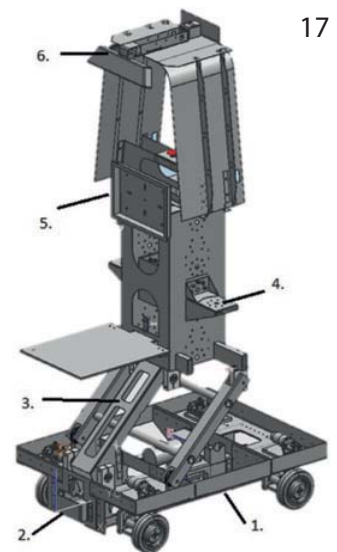
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EDITORIAL

MERGING HIGH-TECH MECHATRONICS AND ROBOTICS



At first glance, it may seem remarkable that Mikroniek publishes a special issue about robotics. Over the years this magazine has been a very useful source of information about state-of-the-art high-tech systems developments, with a sharp eye towards upcoming technologies in the high-tech sector. And it may seem that high-tech systems and precision mechatronic systems have very little in common with robotics. But there are more similarities than one might expect. The design process of robotic systems has a lot in common, for example, with that of lithographic machines and other complex mechatronic systems. So, I feel this is a very timely special issue.

While we all know that industrial robots are used in car manufacturing and other mass production operations, a new class of robotic applications will enter our world, in industry as well as at home. Unlike the classic industrial robot applications, where robots operate in a shielded environment for safety reasons, modern robots will operate in the proximity of humans and animals, so that safety has to be guaranteed. These robots will collaborate with humans and with each other, for example by using modern 3D vision systems. The control systems driving these robots will gracefully adapt their trajectory and motion planning when an operator or an obstacle unexpectedly enters their working area. And most importantly, these robot control systems will be able to deal with uncertainties, such as uncertainty about the quality of vision-based object data, or uncertainties induced by the mechatronic parts of the robot. So the complexity of technological aspects involved in the development of modern robot system is different but comparable to that of complex mechatronic equipment.

The knowledge of how to create very accurate, almost perfect mechatronic systems is a major strength of the Eindhoven region. While the aim of accurate mechatronic design is to minimise uncertainties by optimising the design of precise machines, robotics engineering takes a different route. Adaptive robotic systems can observe the environment, for example through a multitude of sensors based on vision or other technologies, in order to locate the objects to be handled and avoid walls, humans and obstacles. While none of these sensors provide absolute reliability, the robot has to plan and move through the environment in a safe way. Probabilistic robotics covers the engineering field and mathematical principles to operate robots in an unpredictable world with imperfect sensors and mechatronics.

So, the question we now face is whether we can build better high-tech mechatronic systems by adopting the design method used for robotics, where over- and underactuation are common and multi-sensor systems and uncertainties dominate the design process and implementation of control systems. Can we indeed make better mechatronic systems by merging the robotics approach into the high-tech machine development process?

That is exactly what I expect to see in the coming years. Robotic principles such as kinematic solutions, multi-sensor systems, and adaptive control systems able to cope with uncertainties will enter into the development of high-tech mechatronic systems.

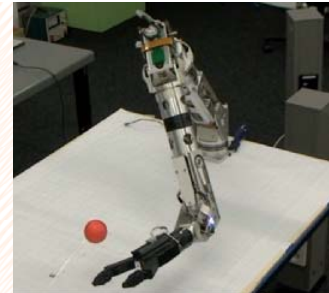
Henk Kiela

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MODELING AND CONTROL ALGORITHMS IN ROBOTICS

Performance, reliability, and competitiveness of the robots on the market are strongly dependent on the expert knowledge involved during the robot development. Professional sustaining of the robots operating in the field does also require specific robotics expertise. In this article, we explain the fundamental algorithms for robot modeling and control. Practical applications of these algorithms are given in the following article.



DRAGAN KOSTIĆ AND PETER VAN DONGEN

Introduction

Independently of their application domain, for example, industry, service, medical, military, sea exploration, rescue, etc., commercial robots are expensive, produced in small series, and have a limited lifetime (maximum ten years). Robot manufacturers are harsh competitors to each other. Performance, reliability, and competitiveness of the robots on the market are strongly dependent on the expert knowledge involved during the robot development. Also professional sustaining of the robots operating in the field does require specific robotics expertise.

Theoretical in-depth knowledge and technological innovations lead to systematic procedures that are beneficial for quality and efficiency improvements, as well

as costs savings, during both the robot design and sustaining activities. These procedures, based on sound theoretical knowledge, involve dedicated model-based robotics methods and algorithms. In this paper, we describe the key algorithms. In the second part of this article, we illustrate applications of the key robotics algorithms in several practical case studies.

First, we recall fundamental steps in the robot development to illuminate the need for the model-based approach. Then, we present systematic modeling algorithms that are generic enough for automatic generation in symbolic form. This form facilitates dynamical analysis, control design, and development of robot control and diagnostics software. The efficient diagnostics is also very important for robot sustaining.

Robot design steps

When developing a robotic system, designers consider a number of use cases for application of their system; for instance, spray-painting, welding, pick & place operations, assembly, etc. Based on their considerations, they anticipate the most challenging tasks that the robot has to perform, in terms of the required workspace, accuracy, speed, and payload. These tasks are needed for derivation of the technical requirements on the robotic system and quality evaluation of the robot design. Since in each task the robot performs certain motions, these tasks are called the benchmark motion tasks for the robot.

AUTHORS' NOTE

Dragan Kostić (Ph.D. thesis, Eindhoven University of Technology (TU/e), the Netherlands, 2004; D. Kostić, B. de Jager, and M. Steinbuch, "Modelling and Identification for Robot Motion Control", pp. 14.1-26, and "Motion Control by Linear Feedback Methods", pp. 15.1-23, both in Th.R. Kurfess (ed.), *Robotics and Automation Handbook*, CRC Press, Boca Raton, Florida, 2004) is mechatronics architect. Peter van Dongen (M.Sc. thesis, "Autonomous 3D grasp planning based on machine vision feedback", TU/e, 2013) is mechatronics engineer. They both work at Segula Technologies Netherlands, based in Eindhoven.

SEGULA Technologies Netherlands is a developer of advanced intelligent systems for the high-tech and automotive industries in the Benelux. As a project organisation, the company applies knowledge of system architecture and modeling, mechanics, mechatronics, electronics, software, system integration and calibration, to the design of nonlinear mechatronic systems. Spearheads include thermal and flow control, robotics and the development of autonomous multi-physics systems.

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The robot development involves the following steps:

1. Definition of the benchmark motion tasks;
2. Computer Aided Design (CAD):
 - a. formulation of the robot kinematics,
 - b. formulation of the robot dynamics without actuators,
 - c. choice of the actuators and conceptual feedback-control design,
 - d. optimisation of the robot inertial properties;
3. Realisation;
4. Final control design;
5. Robot software development;
6. Requirements verification.

After specification of the benchmark motion tasks, the robot design using CAD software begins together with the modeling and analysis activities performed in steps 2a-d. To accommodate the requirements of the benchmark motion tasks, one has to determine the suitable number of degrees of freedom (joints) for the robot, the kinematic configuration of the joints and their motion ranges; these kinematic factors are considered in step 2a of the robot development.

Typically, the designers consider several concepts for the robot kinematics. For evaluation of the candidate concepts, models of the robot kinematics are required to relate motions in the robot joints with the workspace motions of the robot mechanism. Such models are used for analytical calculations, simulations and animations, in order to determine ranges of the joint motions, velocities and accelerations in the benchmark motion tasks. Since the benchmark motions are the most aggressive ones required from the robot, the corresponding joint trajectories determine the limiting values for a given concept of the robot kinematics. The candidate concept characterised by the lowest limits is the most appealing one from the kinematic point of view. The model-based analysis of the robot kinematics is thus the essential part of step 2a.

Once the kinematics is defined, dynamics of the candidate robot design is modeled in step 2b to relate motions in the robot joints with the forces and torques to be supplied by the robot actuators. By tuning mass and inertia parameters of the robot mechanics, which are determined by material properties of the robot parts and their mass distributions, the designers can refine their CAD schematics such as to achieve the desired mechanical stiffness and payload robot characteristics with lower levels of the actuation forces and torques. The model-based dynamical simulations are hence crucial for successful realisation of step 2b.

Results of this step are instructive for optimal selection of the robot actuators in step 2c. The torque/force capability of the robot actuators, gearbox ratios and stiffness of the corresponding drive-train mechanisms are determined such as to accommodate the required force and torque ranges.

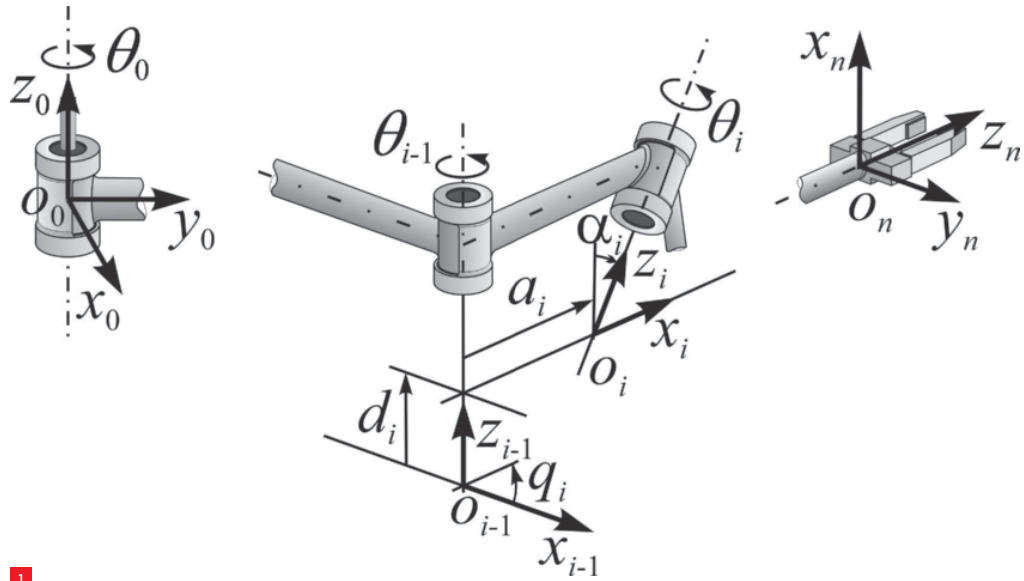
In step 2d, fine-tuning of the robot inertial characteristics is performed to accommodate requirements on the robot motion performance, such as repeatability and precision in the benchmark motion tasks, as well as robustness against deformations due to stresses in mechanical parts. Here, focus is on stiffness and damping characteristics of the robot parts that have critical influence on the motion performance and stress characteristics.

Finite-element models (FEMs) of the critical robot parts are made and then used and analysed in simulations. In this phase, the robot model derived in step 2c is extended with spring/damper elements to capture the non-rigid dynamics due to presence of flexibilities in the robot mechanics. Moreover, co-simulations of the extended robot model with FEMs of the critical parts (for example, robot gripper or flexible mechanical pedestal) are performed to evaluate the robot performance for given stiffness/damping characteristics of the non-rigid mechanical parts. These model-based simulations reveal weaknesses in the existing robot design and trigger corrective actions in a systematic and theoretically sound fashion. Such simulations are instructive not only during development of new robots, but are also very valuable for diagnostics of root causes of performance and reliability issues observed with already deployed robots.

Systematic accomplishment of steps 2a-d ultimately enhances the chances that realisation of the robot hardware and software in steps 3-5 will be followed by successful verification of all the requirements at the end of the robot development process.

Mathematical formulation

In this section we briefly present the fundamental models of the robot kinematics and dynamics that are required for systematic design of robot mechanics, actuation, control software, diagnostics, and dynamical performance analysis. For theoretical background of these models the reader is referred to [1,2]. Here, focus is on mathematical formulations that are suitable for practical implementation. We first model kinematics of the robots. Then, we describe the Jacobian matrix and explain its application for calculation of setpoint trajectories for the robot joints. After that we explain modeling of the robot dynamics by means of Lagrange-Euler equations of motion. An application of



1

1 Fractions of a robotic mechanism with n joints.

these equations for the robot motion control design is illustrated at the end of this section.

Kinematic modeling

Consider a robot mechanism with n degrees of freedom (DoFs), in which each DoF is represented by a revolute or prismatic joint. In Figure 1, we depict fractions of the mechanism with several revolute DoFs. Several coordinate frames are assigned to this mechanism.

A minimal kinematic parameterisation for the robot mechanism can be established using the Denavit-Hartenberg's (DH) convention [1,2]. This convention prescribes a method for assigning the coordinate frames:

1. Assign z_i to be the axis of actuation for joint $i+1$; it is convenient if z_n coincides with z_{n-1} .
2. Choose x_0 and y_0 such that frame $o_0x_0y_0z_0$ in the robot base is right-handed; $o_0x_0y_0z_0$ is the reference (inertial) coordinate frame of the robot.
3. Iteratively assign frame $o_ix_iy_iz_i$ depending on frame $o_{i-1}x_{i-1}y_{i-1}z_{i-1}$ for $i = 1, 2, \dots, n-1$, using a standard algorithm which can be found in [1] and [2].

Using the DH convention, mutual position and orientation of two neighboring coordinate frames $o_{i-1}x_{i-1}y_{i-1}z_{i-1}$ and $o_ix_iy_iz_i$ are uniquely determined by only four kinematic parameters: twist angle α_i , link length a_i , joint angle θ_i , and link offset d_i . These so-called DH parameters are indicated in Figure 1 and are determined as follows:

- a. α_i is the angle between z_{i-1} and z_i measured in the plane normal to x_i (right-hand rule);
- b. a_i is the distance from z_{i-1} to z_i measured along x_i ;

- c. θ_i is the angle from x_{i-1} to x_i measured in the plane normal to z_{i-1} (right-hand rule);
- d. d_i is the distance from origin of frame $i-1$ to the intersection of x_i with z_{i-1} , measured along z_{i-1} .

Cartesian coordinates of the origin o_i of frame $o_ix_iy_iz_i$ relative to frame $o_{i-1}x_{i-1}y_{i-1}z_{i-1}$ are determined by:

$$\mathbf{o}_i^{i-1} = [a_i \cos \theta_i \quad a_i \sin \theta_i \quad d_i]^T \quad (1)$$

In this paper, index in the superscript, e.g. ' $i-1$ ' in \mathbf{o}_i^{i-1} , indicates the reference coordinate frame; T denotes the transpose of a vector or matrix. Orientation of $o_ix_iy_iz_i$ relative to $o_{i-1}x_{i-1}y_{i-1}z_{i-1}$ is represented by the rotation matrix:

$$\mathbf{R}_i^{i-1} = \begin{bmatrix} \cos \theta_i & -\sin \theta_i \cos \alpha_i & \sin \theta_i \sin \alpha_i \\ \sin \theta_i & \cos \theta_i \cos \alpha_i & -\cos \theta_i \sin \alpha_i \\ 0 & \sin \alpha_i & \cos \alpha_i \end{bmatrix} \quad (2)$$

The columns of \mathbf{R}_i^{i-1} represent projections of the unit vectors of axes x_p , y_p , and z_i onto the frame $o_{i-1}x_{i-1}y_{i-1}z_{i-1}$, respectively. In compact form, the position and orientation of the two frames can be described by the so-called homogenous transformation matrix:

$$\mathbf{T}_i^{i-1} = \begin{bmatrix} \mathbf{R}_i^{i-1} & \mathbf{o}_i^{i-1} \\ \mathbf{0}_3^T & 1 \end{bmatrix} \quad (3)$$

Here $\mathbf{0}_3 = [0 \ 0 \ 0]^T$. If joint i is prismatic, then d_i describes the translational DoF of this joint; for a revolute joint, θ_i is the angular DoF.

Let's collect the robot DoFs in a column vector:

$$\mathbf{q} = [q_1 \dots q_n]^T \quad (4)$$

Here, $q_i = d_i$ holds for the prismatic joint and $q_i = \theta_i$ for the revolute one. Since each robot joint has one DoF only, \mathbf{T}_i^{q-1} in (3) has only one variable q_i .

The forward kinematics model describes Cartesian position \mathbf{o}_i^0 and orientation \mathbf{R}_i^0 of the robot coordinate frame $o_i x_i y_i z_i$ relative to the inertial one $o_0 x_0 y_0 z_0$:

$$\mathbf{T}_i^0(\mathbf{q}) = \mathbf{T}_1^0(q_1) \cdot \mathbf{T}_2^0(q_2) \cdot \dots \cdot \mathbf{T}_i^0(q_i) = \begin{bmatrix} \mathbf{R}_i^0(\mathbf{q}) & \mathbf{o}_i^0(\mathbf{q}) \\ \mathbf{0}_3^T & 1 \end{bmatrix} \quad (5)$$

It is practical to assign the last frame $o_n x_n y_n z_n$ to the most distal part of the robot mechanism, for example gripper or tool, and then use (5) to calculate position \mathbf{o}_n^0 and orientation \mathbf{R}_n^0 of that part relative to $o_0 x_0 y_0 z_0$ for a given robot configuration specified by the joint coordinates in vector \mathbf{q} .

In practice, the desired motion of $o_n x_n y_n z_n$ is often given as a function of time t and one has to determine the corresponding trajectories $q_i(t)$ in the robot joints. This is the problem of inverse kinematics (IK), which cannot easily be solved in a general case due to nonlinear nature of functions $\mathbf{o}_n^0(\mathbf{q})$ and $\mathbf{R}_n^0(\mathbf{q})$. Resolving this inherent nonlinearity is especially challenging if the joint motions have to be computed online.

In this paper, we present a solution to the IK problem at the level of robot velocities instead of motions. In particular, we recommend an IK algorithm described in [2], since it is practical for real-time applications and can be applied to any robot kinematics with an arbitrary number of DoFs. This algorithm makes use of the robot Jacobian matrix, so we have to define this matrix first.

Formally known as the manipulator Jacobian, matrix \mathbf{J} relates velocities $\dot{\mathbf{q}}$ in the robot joints (' $\dot{\cdot}$ ' above \mathbf{q} denotes time-derivative) with column vectors \mathbf{v}_n^0 and $\boldsymbol{\omega}_n^0$ of translational and angular velocities, respectively, of the frame $o_n x_n y_n z_n$ relative to $o_0 x_0 y_0 z_0$:

$$\begin{bmatrix} \mathbf{v}_n^0 \\ \boldsymbol{\omega}_n^0 \end{bmatrix} = \mathbf{J}(\mathbf{q}) \dot{\mathbf{q}} \quad (6)$$

Here, $\mathbf{v}_n^0 = \dot{\mathbf{o}}_n^0$, while $\boldsymbol{\omega}_n^0 = [\omega_{x,n}^0 \ \omega_{y,n}^0 \ \omega_{z,n}^0]^T$ is determined by:

$$\mathbf{S}(\boldsymbol{\omega}_n^0) = \begin{bmatrix} 0 & -\omega_{z,n}^0 & \omega_{y,n}^0 \\ \omega_{z,n}^0 & 0 & -\omega_{x,n}^0 \\ -\omega_{y,n}^0 & \omega_{x,n}^0 & 0 \end{bmatrix} = \dot{\mathbf{R}}_n^0(\mathbf{q})(\mathbf{R}_n^0(\mathbf{q}))^T \quad (7)$$

Vectors \mathbf{v}_n^0 and $\boldsymbol{\omega}_n^0$ are functions of time, since according to (6) both depend on time-varying joint motions and

velocities. To calculate \mathbf{J} , we partition this $6 \times n$ matrix into two $3 \times n$ submatrices, \mathbf{J}_v and \mathbf{J}_ω . We denote columns of \mathbf{J}_v and \mathbf{J}_ω by $\mathbf{j}_{v,i}$ and $\mathbf{j}_{\omega,i}$ respectively ($i = 1, 2, \dots, n$):

$$\mathbf{J} = \begin{bmatrix} \mathbf{J}_v \\ \mathbf{J}_\omega \end{bmatrix} = \begin{bmatrix} \mathbf{j}_{v,1} & \dots & \mathbf{j}_{v,n} \\ \mathbf{j}_{\omega,1} & \dots & \mathbf{j}_{\omega,n} \end{bmatrix} \quad (8)$$

To compute $\mathbf{j}_{v,i}$ and $\mathbf{j}_{\omega,i}$ we use column vectors \mathbf{o}_i^0 and \mathbf{z}_i^0 from (5), where \mathbf{z}_i^0 denotes the third column of \mathbf{R}_i^0 :

$$\mathbf{j}_{v,i} = \begin{cases} \mathbf{z}_{i-1}^0 \times (\mathbf{o}_i^0 - \mathbf{o}_{i-1}^0) & \text{for revolute joint } i, \\ \mathbf{z}_{i-1}^0 & \text{for prismatic joint } i; \end{cases} \quad (9)$$

$$\mathbf{j}_{\omega,i} = \begin{cases} \mathbf{z}_{i-1}^0 & \text{for revolute joint } i, \\ \mathbf{0}_3 & \text{for prismatic joint } i. \end{cases} \quad (10)$$

In (9), ' \times ' denotes the cross-product of two column vectors. It is important to notice that once the forward kinematics (5) is computed, then it is straightforward to calculate the manipulator Jacobian using (9) and (10).

Since the IK algorithm calculates the joint velocities, the corresponding joint motions have to be determined by numerical integration. Online calculations of \dot{q}_i and q_i are performed at discrete-time instants $t_k = kT_s$ on a digital processor, where T_s is the sampling time and k is a positive integer. To minimise numerical errors due to discrete-time integration, a feedback mechanism has to be embedded into the IK algorithm, which is explained next. We denote by $\mathbf{o}_{n,r}^0$ and $\mathbf{R}_{n,r}^0$ the desired position and orientation of the last robot coordinate frame. By \mathbf{x}_n^0 , \mathbf{y}_n^0 and \mathbf{z}_n^0 we denote the first, second and third column of \mathbf{R}_n^0 , respectively; the columns of $\mathbf{R}_{n,r}^0$ are $\mathbf{x}_{n,r}^0$, $\mathbf{y}_{n,r}^0$ and $\mathbf{z}_{n,r}^0$. At each t_k , the feedback mechanism compares $\mathbf{o}_{n,r}^0(t_k)$ and $\mathbf{R}_{n,r}^0(t_k)$ with \mathbf{o}_n^0 and \mathbf{R}_n^0 , respectively, that are computed via (5) using the IK solution \mathbf{q} found at t_{k-1} . For this, the following 3×1 Cartesian \mathbf{e}_{xyz} and orientation \mathbf{e}_{rot} errors are used:

$$\mathbf{e}_{xyz}(t_k) = \mathbf{o}_{n,r}^0(t_k) - \mathbf{o}_n^0(\mathbf{q}(t_{k-1})) \quad (11)$$

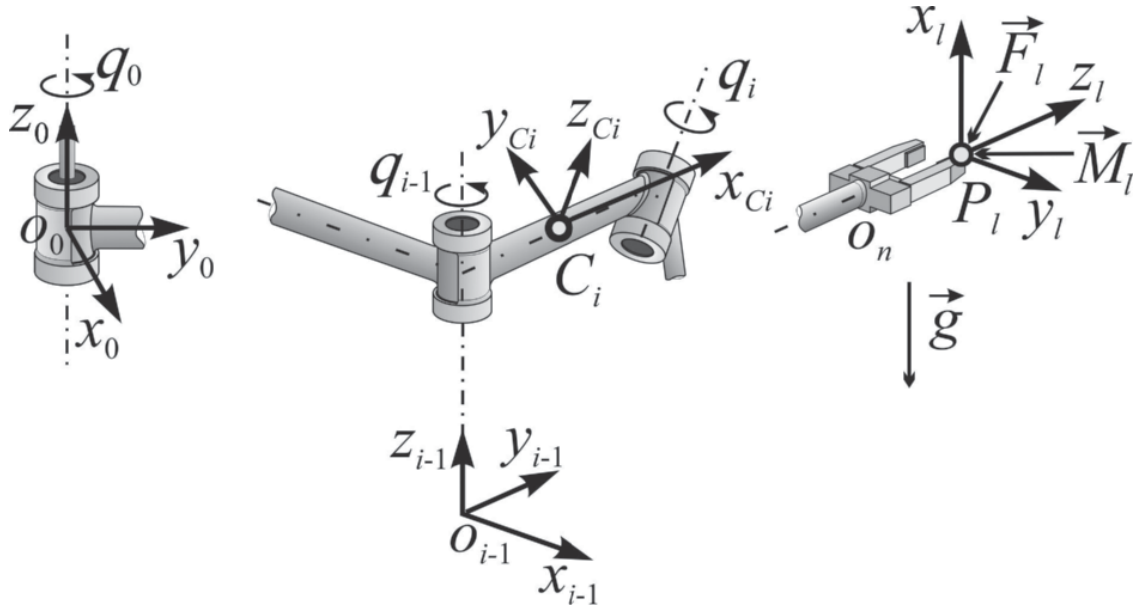
$$\mathbf{e}_{rot}(t_k) = 0.5 [\mathbf{x}_n^0(\mathbf{q}(t_{k-1})) \times \mathbf{x}_{n,r}^0(t_k) + \mathbf{y}_n^0(\mathbf{q}(t_{k-1})) \times \mathbf{y}_{n,r}^0(t_k) + \mathbf{z}_n^0(\mathbf{q}(t_{k-1})) \times \mathbf{z}_{n,r}^0(t_k)] \quad (12)$$

It can be proven that the time-derivative of \mathbf{e}_{rot} equals:

$$\dot{\mathbf{e}}_{rot} = \mathbf{L}^T \boldsymbol{\omega}_{n,r}^0 - \mathbf{L} \mathbf{J}_\omega(\mathbf{q}) \dot{\mathbf{q}}$$

Here:

$$\mathbf{L}(t_k) = -0.5 [\mathbf{S}(\mathbf{x}_{n,r}^0(t_k)) \mathbf{S}(\mathbf{x}_n^0(\mathbf{q}(t_{k-1}))) + \mathbf{S}(\mathbf{y}_{n,r}^0(t_k)) \mathbf{S}(\mathbf{y}_n^0(\mathbf{q}(t_{k-1}))) + \mathbf{S}(\mathbf{z}_{n,r}^0(t_k)) \mathbf{S}(\mathbf{z}_n^0(\mathbf{q}(t_{k-1})))] \quad (13)$$



2

Here, \mathbf{S} is 3×3 skew-symmetric matrix as the one given by (7). As already mentioned, the IK algorithm computes the joint velocities first and then calculates the joint motions via numerical integration:

$$\dot{\mathbf{q}}(t_k) = \begin{bmatrix} \mathbf{J}_v(\mathbf{q}(t_{k-1})) \\ \mathbf{L}(t_k) \mathbf{J}_\omega(\mathbf{q}(t_{k-1})) \end{bmatrix}^\dagger \cdot \begin{bmatrix} \dot{\mathbf{o}}_{n,r}^0(t_k) + \mathbf{K}_{xyz} \mathbf{e}_{xyz}(t_k) \\ \mathbf{L}^{-1}(t_k) (\mathbf{L}^T(t_k) \boldsymbol{\omega}_{n,r}^0(t_k) + \mathbf{K}_{rot} \mathbf{e}_{rot}(t_k)) \end{bmatrix} \quad (14a)$$

$$\mathbf{q}(t_k) = \mathbf{q}(t_{k-1}) + \dot{\mathbf{q}}(t_k)(t_k - t_{k-1}) \quad (14b)$$

In (14a), “ \dagger ” denotes matrix inverse if the robot has $n = 6$ DoFs. If $n > 6$, the robot has more DoFs than required for reaching the desired $\mathbf{o}_{n,r}^0$ and $\mathbf{R}_{n,r}^0$ (kinematic redundancy); in this case, \mathbf{J}_v and \mathbf{J}_ω in (14a) have more columns than rows and “ \dagger ” represents the Moore–Penrose matrix pseudoinverse [1]. Diagonal 3×3 matrices \mathbf{K}_{xyz} and \mathbf{K}_{rot} in (14a) contain positive gains on their main diagonals. By tuning these gains, we minimise errors (11) and (12) that may appear due to numerical integration in (14b).

At this point, we have completed kinematic modeling. Dynamic modeling is considered next.

Dynamic modeling

A model of the robot dynamics relates motions, velocities and accelerations in the robot joints, on one hand, and input torques and forces applied to revolute and prismatic joints, respectively, on another. Before presenting computation of this model for a given robotic mechanism with n DoFs, we introduce several ingredients of this model with a reference to Figure 2.

2 Link i of a robotic mechanism with n joints.

In Figure 2 we can notice the i -th robot link of mass m_i whose center of mass is located at point C_i ; the coordinate frame $C_i x_{C_i} y_{C_i} z_{C_i}$ is attached to this link with the origin at C_i . Cartesian position $\mathbf{o}_{C_i}^0$ and orientation $\mathbf{R}_{C_i}^0$ of $C_i x_{C_i} y_{C_i} z_{C_i}$ relative to $o_0 x_0 y_0 z_0$ are computed using the relationship similar to the one given by (5): only $\mathbf{T}_i^{i-1}(\mathbf{q}_i)$ from (5) is substituted by a homogenous transformation matrix $\mathbf{T}_{C_i}^{i-1}(\mathbf{q}_i)$ describing position and orientation of $C_i x_{C_i} y_{C_i} z_{C_i}$ relative to $o_{i-1} x_{i-1} y_{i-1} z_{i-1}$. We denote by $\mathbf{J}_{v_{C_i}}$ and $\mathbf{J}_{\omega_{C_i}}$ Jacobian matrices that via (6) relate the robot joint velocities with translational and angular velocities of $C_i x_{C_i} y_{C_i} z_{C_i}$; these Jacobian matrices can be calculated in an equivalent way as described by the algorithm (6)-(10). By \mathbf{J}_i we denote an inertia tensor of link i :

$$\mathbf{J}_i = \begin{bmatrix} J_{xx,i} & J_{xy,i} & J_{xz,i} \\ J_{yx,i} & J_{yy,i} & J_{yz,i} \\ J_{zx,i} & J_{zy,i} & J_{zz,i} \end{bmatrix} \quad (15)$$

The tensor contains the link mass moments of inertia on the main diagonal and cross-moments of inertia elsewhere in the matrix. If axes of the frame $C_i x_{C_i} y_{C_i} z_{C_i}$ are aligned with the principal axes of inertia for this link, then \mathbf{J}_i contains only the principal mass moments of inertia. Besides forces and torques supplied by the actuators for the robot DoFs, the robot mechanism can be subject to external force \vec{F}_l and moment \vec{M}_l at any contact point P_l with the environment, see Figure 2. Let us assume m interaction points, i.e., $l \in \{1, \dots, m\}$. To model dynamics of the robot subject to \vec{F}_l and \vec{M}_l , we need Jacobian matrix \mathbf{J}_{p_l} , which relates the joint velocities with translational and angular ones of the coordinate frames $P_l x_{P_l} y_{P_l} z_{P_l}$ attached to the robot mechanism at the contact point. This $6 \times n$ Jacobian can be computed by the algorithm (5)-(10).

To model the robot dynamics we use the standard Euler-Lagrange representation [1,2]:

$$D(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q) + f(q, \dot{q}) + \sum_{l=1}^m J_{P_l}^T(q)T_l = \tau \quad (16)$$

Here, D is an $n \times n$ inertia matrix, \ddot{q} is a vector of the joint accelerations, $C\dot{q}$, g and f are n -dimensional column vectors of centripetal/Coriolis, gravity/elastic, and friction effects, respectively, $T_l = [F_l^T \ M_l^T]^T$ is a column vector of external forces F_l and moments M_l (both F_l and M_l have three elements), and τ is an n -dimensional column vector of the forces and torques applied to the robot joints. The inertia matrix D is computed as follows:

$$D(q) = \sum_{i=1}^n \left\{ m_i J_{v_{C_i}}^T(q) J_{v_{C_i}}(q) + J_{\omega_{C_i}}^T(q) R_{C_i}^0(q) J_{C_i}(R_{C_i}^0(q))^T J_{\omega_{C_i}}(q) \right\} \quad (17)$$

If we denote by d_{ij} an element of D , $i, j \in \{1, \dots, n\}$, then we can determine elements c_{kj} of the $n \times n$ matrix C appearing in (16), $k, j \in \{1, \dots, n\}$ as follows:

$$c_{kj}(q, \dot{q}) = \sum_{i=1}^n c_{ij,k}(q) \dot{q}_i \quad (18)$$

Here:

$$c_{ij,k}(q) = c_{j,i,k}(q) = 0.5 \left\{ \frac{\partial d_{kj}(q)}{\partial q_i} + \frac{\partial d_{ki}(q)}{\partial q_j} - \frac{\partial d_{ij}(q)}{\partial q_k} \right\}$$

To calculate elements of g in (16), we determine first the total potential energy of the robot mechanism. The nominal source of the potential energy is gravity. Let us denote by $g^0 = [g_x^0 \ g_y^0 \ g_z^0]^T$ the vector giving the direction of gravity \vec{g}^0 in the inertial robot frame $o_0x_0y_0z_0$, see Figure 2. If elastic elements are present in the robot mechanism, for example flexible joints and non-rigid links, then each additional robot DoF induced by the elasticity can be represented by a linear or torsional spring; type of the spring depends on whether the particular elasticity causes translational or angular robot motions. Let us assume that the elastic elements introduce f additional DoFs, and denote by λ_j a motion coordinate (translational or angular displacement) of the j -th additional DoF, $j \in \{1, \dots, f\}$; by k_j we denote stiffness of the corresponding spring. Then, the total potential energy of the robot is the sum of the robot potential energy due to gravity and potential energy stored in all elastic elements:

$$P(q) = \sum_{i=1}^n m_i (g^0)^T o_{C_i}^0(q) + 0.5 \sum_{j=1}^f k_j \lambda_j^2 \quad (19)$$

For convenience, we can consider that the vector q in (4) already contains both the nominal and elastic DoFs. Then, elements g_k of g in (16) can be computed as follows:

$$g_k(q) = \frac{\partial P(q)}{\partial q_k}, \quad k \in \{1, \dots, n\} \quad (20)$$

Friction modeling and compensation are important topics in robotics, since the friction effects may have significant influence on selection of the robot actuators and robot motion performance. Here, it is sufficient to mention that type and complexity of a friction model are determined by actual purpose of the robot modeling; in the robot development phase, simple friction models are often good enough since the focus is on the nominal robot behaviour. The basic model comprises Coulomb and viscous friction effects only:

$$f_k(q_k, \dot{q}_k) = f_{c,k} \text{sign}(\dot{q}_k) + f_{v,k} \dot{q}_k, \quad k \in \{1, \dots, n\} \quad (21)$$

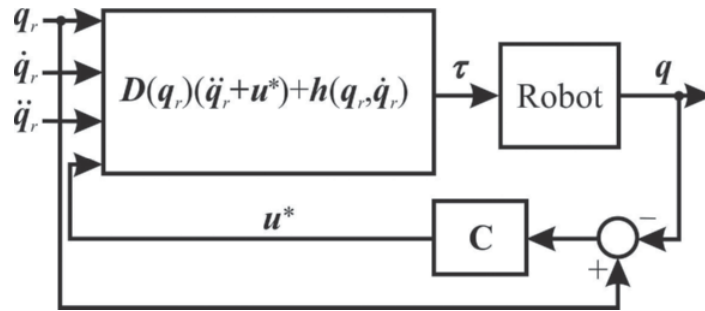
Here, f_k is an element of vector f in (16), $f_{c,k}$ and $f_{v,k}$ are the coefficients of the Coulomb and viscous friction, respectively, and $\text{sign}(\cdot)$ is a standard sign function. For more information about friction modeling and compensation techniques the reader is referred to [3,4].

The column vector τ in (16) contains torques and forces that are externally applied for actuation of the revolute and prismatic joints, respectively. These are the inputs to the model (16) of the robot dynamics. If not all robot joints are actuated, then the corresponding elements of τ are equal to zero; for instance, the robot DoFs induced by the flexibilities have no additional actuation besides the associated springs. As for the actuated DoFs, their inputs are supplied by the robot actuators. Actuator modeling is beyond the scope of this paper; more information about this topic can be found in [1,2].

Model-based robot control

In the classical robot motion control, each actuated robot joint is considered as a separate control plant for which an individual servo-controller is designed. For an actuated joint k , the plant dynamics is often described by a transfer function from the input torque or force τ_k to the corresponding joint displacement q_k ; in practice, this transfer can be determined by frequency response (frf) measurements.

Since dynamics of the robot are nonlinear functions of the joint positions, velocities and accelerations, see (16), the transfer functions determined at different robot configurations have in general different magnitude and phase characteristics. Consequently, any classical control design has to ensure stability robustness for all variations in



3

3 Model-based robot motion control architecture.

the plant dynamics which typically limits the resulting servo-control bandwidth and motion control performance. Moreover, dynamic couplings between different robot axes are treated as external disturbances that have to be suppressed by individual control loops. That imposes additional constraints on stability robustness and performance in classical control.

Limitations of the classical approach can be alleviated by model-based control design. In Figure 3, we depict a servo-control architecture in which the robot model (16) is explicitly used via terms D and $h = C\dot{q} + g + f$. In this architecture, q_r denotes the setpoint motion variables and C is an $n \times n$ transfer function matrix of feedback servo controllers that generate vector u^* of feedback control signals. This architecture is known as an inverse dynamics control [1,2], since it utilises a model-based compensation for the nonlinear robot dynamics. The main effort of the feedback control action u^* is on compensation for decoupled and configuration-independent dynamics in the robot joints. That enables higher servo-control bandwidth settings and better motion control performance in comparison with the classical control approach.

Automatic model derivation in compact form

Derivation of the kinematic and dynamic models can be automated by implementing the algorithms described in the previous sections in any software for manipulation of mathematical expressions in symbolic form. Some examples of software packages that enable symbolic computations are Maple [5], Mathematica [6], and Symbolic Math Toolbox [7].

At Segula Technologies Netherlands, we use an intuitive software tool for automatic robot modeling. Its inputs are kinematic and inertial parameters of a given robotic mechanism: DH parameters, masses, coordinates of the center of masses, inertia tensors, and stiffness coefficients of elastic elements. For the given settings, this tool automatically computes symbolic expressions of the robot

forward kinematics, manipulator Jacobian and Lagrange-Euler equations of motion. The resulting models are represented in compact form thanks to automatic substitution of all trigonometric functions and common mathematical expressions with variables that are computed only once. For illustration, our tool can automatically represent formula (22) into the computationally far more efficient compact form (23):

$$A = (\sin(5x) + \cos x)^2 + 3x(\sin(5x) + \cos x) \quad (22)$$

$$D_1 = \sin(5x), D_2 = \cos x, D_3 = D_1 + D_2 \quad (23)$$

$$A = D_3^2 + 3xD_3$$

With this software we can convert symbolic expressions requiring several megabytes of storage into an embedded software routine which occupies only a hundred of kilobytes. A particular algorithm for conversion of symbolic expressions into the compact form can be found in [8]. The compact model representation is essential for time-efficient computer simulations and embedded software implementations of the robot models.

Conclusion

This paper explains purpose, derivation, and different applications of kinematic and dynamic models in robotics. It is emphasised that for the first-time-right outcome of the robot development process, it is essential to use the models in all phases of that process. Model-based analysis and simulations enable systematic and optimal design of the robot kinematics, actuation, inertial properties, trajectory generation, servo control, etc.

Mathematical algorithms behind the key robot models are explained in detail using a framework which greatly facilitates automatic model derivation using any software for symbolic computation. These algorithms are used at Segula Technologies Netherlands for generation of computationally efficient robot models and embedded control software.

Several applications of the models in robotics practice are given in our second article in this issue.

The modeling and simulation techniques described in this paper are also valuable for sustaining of legacy products. Model-based analysis of the robots that are already deployed in the field is a way to reveal root causes of their downtimes and accelerate troubleshooting. Especially on items like wear of parts and unexpected behaviour.

Finally, we point out that the modeling and analysis framework presented in this paper is directly applicable in other domains beyond the robotics. Think of model-based system design optimisation and development of diagnostic and embedded control software for electronic microscopes, MRI scanners, lithographic machines, automotive systems, pick & place machines, gantry systems, and medical systems, such as automated surgical tools, active endoscopes, orthoses, exoskeletons, etc. ■

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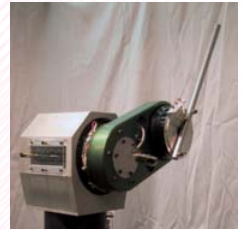
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MODELING AND CONTROL ALGORITHMS IN ROBOTICS

The key algorithms for robot modeling and control were presented in the previous article. They are essential for professional development of the robot hardware and software, as well as for sustaining of the robots that are already deployed in the field. Here, we illustrate the application of these algorithms in practice for robot design optimisation, performance analysis, and servo control.

DRAGAN KOSTIĆ AND PETER VAN DONGEN



Introduction

The need for robot modeling during development of the robot hardware and software was explained in our first article in this issue. There, a reader can find fundamental models of the robot kinematics and dynamics together with a generic model-based servo-control architecture. Merits of model-based sustaining of the legacy products are also described.

In this article, we demonstrate utilisation and merits of the robot models in several illustrative case studies from practice. We show first how simulations of robot dynamics can be used to improve the design of an industrial robot for handling substrates. Then, we present an online motion planner for a kinematically redundant robotic arm. Finally, we give an example of motion performance improvement of a highly nonlinear robot with direct-drive actuation thanks to the model-based servo-control approach.

Model-based robot design optimisation

Our first case study concerns a collaboration between Segula Technologies Netherlands and VDL ETG on the development of a new robot for semiconductor equipment. This robot is intended for very fast and accurate handling of substrates in the horizontal plane. The initial robot design and pilot prototype come from an external supplier, as a further development of an existing equipment. This development is driven by much more stringent performance requirements on the robot than in the past. Measurements carried out on that prototype have revealed that adaptations of the robot become necessary, in order to meet these new and highly demanding requirements. Our objective is to improve the original design, such as to fulfill the new requirements especially on the positioning

Segula-VDL ETG collaboration

Segula Technologies Netherlands collaborates with VDL Enabling Technologies Group on the development of robotic applications. Segula develops and maintains robotics competences used in joint development projects with VDL ETG.

VDL ETG, with headquarters in Eindhoven, the Netherlands, is a tier-one contract manufacturing partner, delivering high-tech capital equipment to leading OEM companies and users of advanced production lines. VDL ETG's services include prototyping, customer-specific factory automation projects and series manufacturing of 'high-mix low-volume' products.

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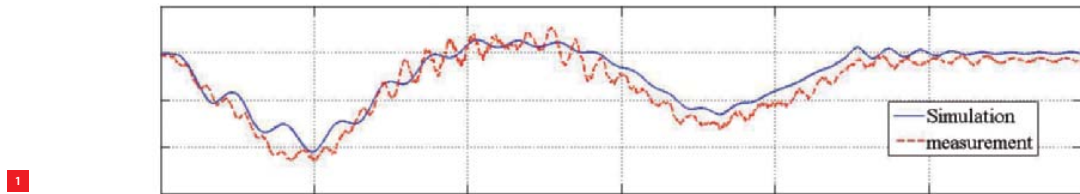
AUTHORS' NOTE

Dragan Kostić is mechatronics architect and Peter van Dongen is mechatronics engineer, both at Segula Technologies Netherlands, based in Eindhoven, the Netherlands.

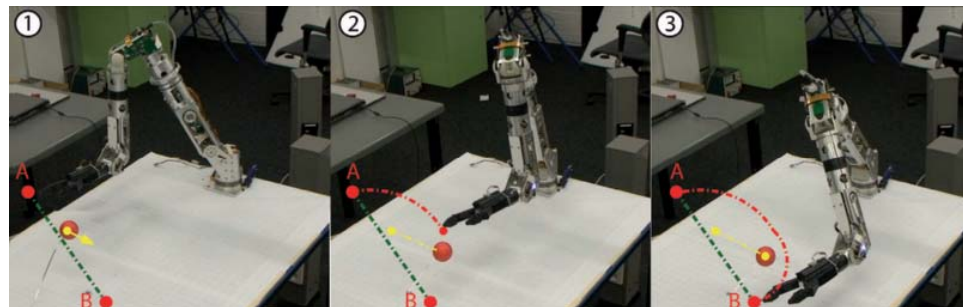
Segula Technologies Netherlands is a developer of advanced intelligent systems for the high-tech and automotive industries in the Benelux.

As a project organisation, the company applies knowledge of system architecture and modeling, mechanics, mechatronics, electronics, software, system integration and calibration, to the design of nonlinear mechatronic systems. Spearheads include thermal and flow control, robotics and the development of autonomous multi-physics systems.

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1



2

1 Measured (red) and simulated (blue) vertical movement of an industrial robot.

2 The gripper of the AMOR arm avoids the moving obstacle (red ball) during motion from point A to point B.

accuracy in all three Cartesian directions. In this example, we are focused on minimisation of parasitic robot movements in the vertical direction, which is not servo controlled.

To optimise the robot design, we derive a model of the robot dynamics, denoted by Equation 16 in the first article, and use this model in simulations to evaluate different choices for redesign of the robot mechanics and control software. Our model describes nonlinear rigid and non-rigid dynamics of the robot mechanics, actuator drive-trains including friction and flexibilities, feedback and feedforward controllers, trajectory generators, and discrete-time sampling effects.

We even integrate a finite-element model (FEM) of the robot gripper into this nonlinear model. Two models are interfaced via very rigid springs that model force interaction between the robot and the gripper dynamics. The interaction forces enter the robot model via the last term on the left-hand side in the aforementioned dynamics model. The initial model parameters correspond to the original robot design and are verified by measurements performed on the pilot prototype.

In Figure 1 we show the displacement which is measured (red plot) in the vertical direction and the corresponding simulation (blue plot) obtained with our model. This sub-millimeter oscillation arises during the horizontal robot movements of almost one meter in length. Despite the fact that horizontal and vertical displacements differ several

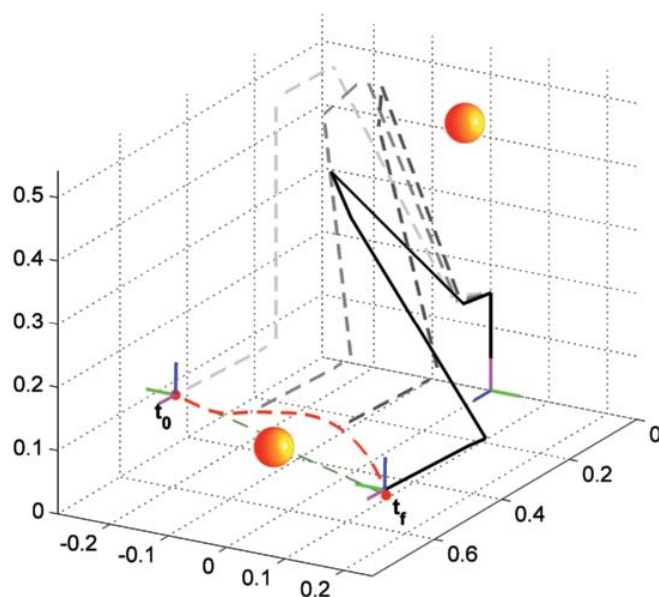
orders in magnitude, our simulation results are very similar with the measurements. That verifies the quality of our model and justifies its use for investigation of different options for the robot redesign.

Using the model-based simulations we have identified several possible improvements in the original design to meet the challenging requirements. Therefore, we have proposed necessary design modifications with each modification validated in simulations. Our redesign proposals should lead to a new robot realisation that will fulfill the new requirements.

Online setpoint trajectory generation

In the second case study, we address setpoint trajectory generation for a kinematically redundant robotic arm. Solving the IK problem (inverse kinematics) for any redundant arm is not straightforward due to increased complexity and dimensionality of the forward kinematics model (Equation 5 in the previous article). It is especially challenging to compute the setpoint trajectories for the robot joints online. The AMOR robotic arm [1], shown in Figure 2, is an example of a kinematically redundant arm since it has seven revolute degrees of freedom (DoFs).

Within the scope of the graduation project documented in [2], an online motion planner was developed for this arm. This planner makes use of the IK algorithm (Equation 14, previous article) to compute the setpoints for the robot joints given the reference workspace trajectory of the robot



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gripper. The motion planner also implements an online adaptation of the gripper trajectory for collision avoidance with static and dynamic obstacles obstructing the reference path of the gripper. In Figure 2 we illustrate online avoidance of a moving obstacle (red ball), which is realised using the motion planner.

Thanks to one redundant DoF, AMOR can hold its gripper at the same workspace location for literally infinitely many joint configurations. Consequently, the arm can move the gripper along the desired workspace trajectory while avoiding collisions between its elbow and other objects in its environment. That feature is also implemented in the motion planner. In Figure 3 we show a simulation result illustrating simultaneous collision avoidance with two obstacles: one on the gripper path and another one obstructing the elbow of the robot.

Model-based robot motion control

In our last case study, we consider the problem of model-based motion control of a direct-drive robot with three revolute joints, depicted in Figure 4.

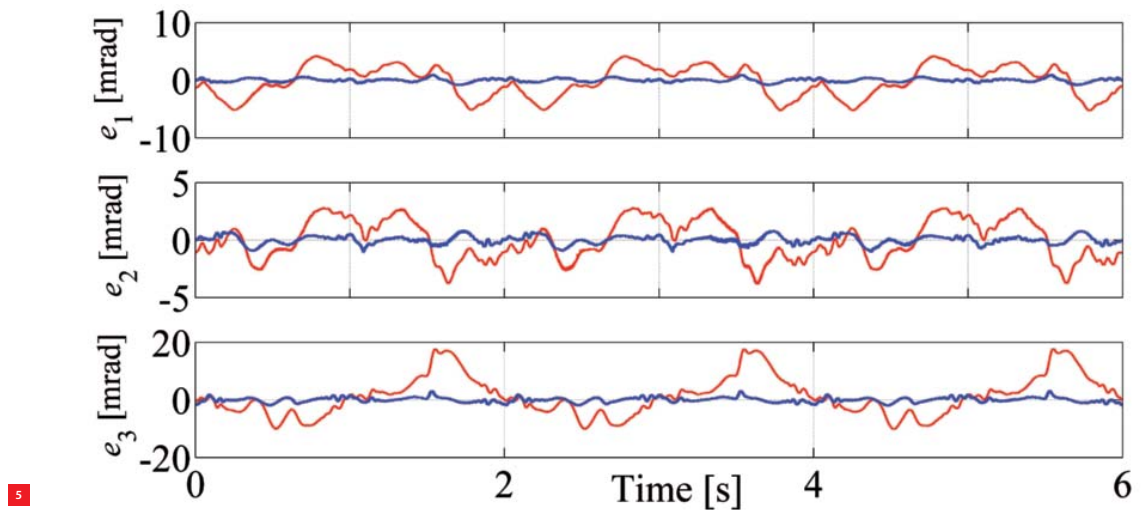
Due to the direct-drive actuation, the robot dynamics are highly nonlinear and coupled: motion of any robot axis causes motions in the other two joints. A nonlinear model of the rigid robot dynamics can be found in [3]. Besides strong nonlinearities, flexibilities, time delay, and measurement noise also affect the robot operation. Challenging dynamics and parasitic effects make this robot

3 Simultaneous avoidance of two obstacles.

4 Robot for motion control benchmarking.

an ideal test bed for benchmarking of different motion control strategies. Here, we compare performance of a classical controller designed by considering dynamics of different robot axes as separate control plants, with the one described by the model-based servo-control architecture depicted in Figure 3 in our first article. Feedback controllers in both designs have the same settings for the sake of fair comparison. Two control designs are tested in the same benchmark motion task in which each robot joint makes a sequence of rapid displacements of 180°, each performed in 1 second. At certain moments during these movements, the robot actuators have to supply their maximum torques.

Figure 5 shows differences (in milliradians) between the reference and measured motions in the robot joints that are achieved with the classical (red plots) and model-based (blue plots) controllers. By inspection of these plots we can observe that the model-based design outperforms the classical one. The performance improvement can be attributed to model-based compensation of nonlinear dynamics. Motion performance of the model-based design can be improved even further by increasing the servo bandwidth of the feedback controller. On the contrary, the classical controller does not admit an additional bandwidth increase due to stability issues caused by nonlinear couplings among the robot axes.



5 Servo-control errors achieved with the classical (red) and model-based (blue) controllers.

Conclusion

We have shown practical applications of the models of robot kinematics and dynamics that were presented in the previous article. The model-based simulations of the robot dynamics, used in our first practical example, facilitate root-cause analysis of parasitic vibrations observed on the real robot and a systematic robot redesign that leads to fulfillment of the new highly demanding requirements.

The inverse kinematics algorithm applied in our second case study enables online generation of the setpoint trajectories for the robot joints and avoidance of dynamic obstacles in the robot neighbourhood.

The model-based servo-control method utilised in our third case study achieves considerable servo-control performance improvement with respect to the conventional feedback motion controller.

The practical examples presented in this article clearly illustrate merits of a model-based approach to robot design optimisation in industry, online setpoint trajectory generation for a robot of complex kinematics, and motion control performance improvement for a robot of highly nonlinear dynamics. ■

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ROBOT ROSE PERFORMING HOME CARE TASKS

ROSE (Remotely Operated Service robot) was developed as a prototype service robot to perform home care tasks. Experiments with ROSE have shown that the development of a service robot for home care is feasible. ROSE was controlled from a distance (8 km) by care givers to perform small tasks for seniors. The ROSE design can also be used for the development of service robots for other domains, e.g. robots to perform security tasks, building maintenance or construction.

MICHEL VAN OSCH, DEBJYOTI BERA, KEES VAN HEE AND HENK ZEEGERS

Service robots are to perform tasks normally done by humans in an environment where humans work as well. However, they do not have to accomplish these tasks in the same way as humans or look like a human being. Ultimately, service robots should be able to autonomously deal with any situation they may encounter. However, currently they can only deal with very specific tasks in very specific situations. In order to make a robot work in a domestic environment, in the coming years a human operator will have to stay in the loop, to take manual control and help the robot from a distance (near or far) to continue on its way, for example when it gets stuck or cornered.

A TSR (Tele-operated Service Robot) is remotely controlled by a human being (an operator) and performs tasks (services), typically in uncontrolled environments. Tele-operation is probably the oldest form of robotics [1], allowing the operator to act remotely as if they were on the spot, for instance by letting the robot copy their

manipulations. However, in order for the robot to be able to compete with a human, the operator should be able to give a simple command to perform a complex task and the robot should be able to perform a task in a reasonable amount of time. Therefore, a TSR also requires autonomy in performing tasks.

The TSR field differs fundamentally from the mature, classical field of industrial robots (see Table 1). A TSR operates in an unknown and unadjusted environment and the operator is not able to specify coordinates. Take the movement needed to open a door, for example: the operator sees the door via a camera on a screen and has to give a command to move to the door, grip the door handle, move that handle downwards, and pull (or push) the door. The operator does not know the coordinates of the door, but communicates through maps and images received from the robot, which have to be translated to coordinates used by the robot internally.

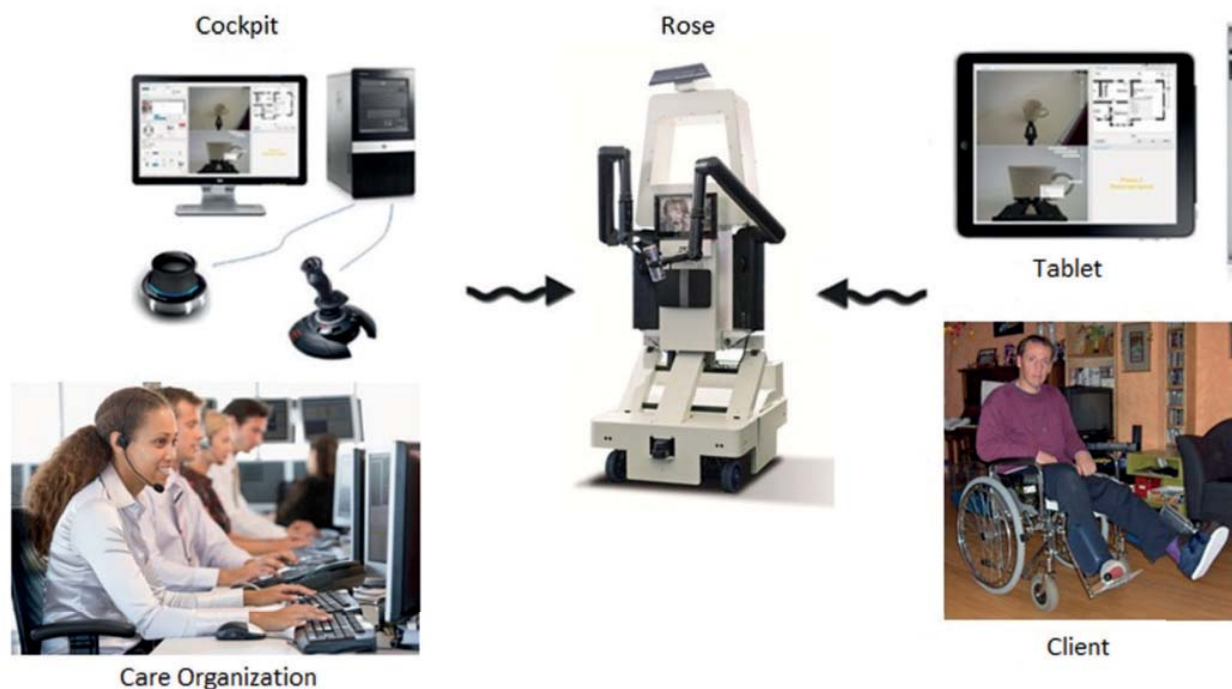
AUTHORS' NOTE

Michiel van Osch, Kees van Hee and Henk Zeegers work with start-up company Rose BV. Debjyoti Bera works at Eindhoven University of Technology. This article is a summary of "Tele-operated service robots: ROSE", *Journal of Automation in Construction*, August 2013, M. van Osch, D. Bera, K. van Hee, Y. Koks and H. Zeegers, August 2013, with the kind permission of Elsevier.

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Table 1. Differences between service robots and industrial robots.

	Service robots	Industrial robots
Tasks	Ad hoc	Programmed
Type of work	Non-routine	Routine
Speed	Relatively low	High
Accuracy	Average	High
Control	Force / Visual Servoing	Position
Range of motion	Free / Rails	Static
Environment	Human	Safety cage



1 Set-up for tele-operation: control of the robot by the master (care centre or client) through a cockpit or handheld device.

A TSR consists of a master and a slave component, the robot executing the remote commands given by the master (see Figure 1). The slave comprises a mobile platform, a vision system, and a set of arms (one, two or even more), each equipped with a gripper. The master is a cockpit, an integrated set of devices that enables the operator to control the slave. In a basic TSR, the operator has to precisely demonstrate the actions to be executed for a task, perhaps at a different scale. In an advanced TSR, the operator has a high-level command language, so that simple commands can be used to order the service robot to perform a complex task. Such a command can be given to the slave by means of advanced input devices such as gloves, joysticks supporting haptic feedback, or voice recognition. An even more advanced TSR is able to learn from past behaviour (programming by example, or supervised learning).

From a study of application domains of tele-operated robots – both in terms of technology and business – ‘home care’ emerged as the most promising domain, mainly because of the urgent social needs (rapidly aging population [2] [3]) and the availability of enthusiastic development partners.

TSR project

This article describes the development of robot ROSE within the TSR project [2]. In 2009, we initiated this project in which a consortium of industries, research partners,

design and engineering companies, a home care organisation and clients developed a tele-operated service robot: ROSE (Remotely Operated Service Robot). The result is able to autonomously move to a location, grab objects, place objects, open doors (for instance the microwave, the fridge, an in-house door), open caps from bottles, clean, handover objects, and grab or place objects with both arms simultaneously. ROSE was tested in a home environment together with care givers and clients. The TSR project ended in 2012. Since the summer of 2013, the development of ROSE is continued by a newly formed start-up, Rose BV, together with field labs in several home-care organisations and clients. Rose BV aims to develop robot ROSE into a product within three years.

An operator can control ROSE from a remote location or the client can control the robot himself with a handheld device. Fully manual control of the robot via input devices like joysticks should always be possible, but tasks can be automated to make control easier for the operator. If the robot cannot manage the task autonomously, the operator can always manually control the robot and may still be able to complete the task in this way.

ROSE only assists elderly and disabled people in domestic tasks; medical tasks are still performed by trained care givers. One operator can help ten people during the day and twenty people at night. As elderly individuals do not need

Table 2. Use cases selected for ROSE.

Use case	Robot task	Test objective
Detecting a person	Moving through the apartment, while the operator sees where the residents are.	Navigating smoothly in a home environment.
Turning on the light	Moving through the apartment and switching on a light.	Manipulating buttons in a home environment.
Moving an obstacle	Moving through the environment and moving an obstacle aside.	Moving objects in the environment using both arms.
Preparing breakfast	Taking a set of breakfast items and bringing them to the client.	Picking and placing a set of differently sized and shaped objects.
Pouring a drink	Pouring milk from a carton into a mug.	Handling liquids and performing more precise tasks.
Preparing a meal	Taking a pre-cooked meal, heating it in an ordinary micro-wave and bringing it to the client on a tray, held by both arms.	Performing even more precise tasks, handling dials and small buttons and using synchronised arm movements.

constant help, the operator can help another client while the robot performs a task autonomously. Two hours of personal home care plus help from ROSE will be less expensive than care in a nursing home, which makes a business case. And three hours of personal home care per day is as expensive as robot ROSE being available day and night. Moreover, a care giver needs to travel to the client.

Use cases

The development of ROSE started with defining the use cases that the robot is supposed to be able to perform. The most cumbersome tasks for care givers are frequent and simple tasks, such as opening curtains, preparing fruit, doing dishes, posting letters. Automating these simple tasks makes their job more attractive and creates time to really engage with the clients. After extensive workshops with both care givers and seniors, we selected a number of representative use cases that are a good reflection of both the technical possibilities and the wishes of the care givers and seniors (see Table 2).

Requirements

These use cases were described in detailed scenarios, which were used for scenario-based testing. Based on these scenarios, we specified the user requirements for the robot (and cockpit):

- Can be operated in an unadjusted home environment: requirements regarding size, task space, and manoeuvrability: the robot must fit through the door, be able to reach objects on the floor and objects in the upper cabinets of the kitchen, and be able to manoeuvre in a crowded environment.
- Can be operated by a care giver: user requirements for the cockpit, for instance the ability to use common interface devices and a simple graphical user interface (GUI).

- Can be operated by clients, for example via a tablet: the tasks that clients can do with the robot may be limited; they can ask help from an operator for performing more complex tasks.
- Safe to its environment and itself.
- Can do tasks autonomously where automation is possible; however, the human operator must always be able to take control of the robot.

These user requirements were translated into mechanical, electronic and software requirements and further developed into a system architecture.

System design

The system consists of the robot and the cockpit. The robot comprises hardware, electronics, and software. The cockpit consists of a PC, control devices, and a GUI.

Robot design

Figure 2 shows the mechanical design of ROSE (the prototype), and Table 3 presents the robot's dimensions. The main components are:

- a four-wheel driven and steered (holonomic) mobile platform (1), developed for steering individual wheels, such that the robot is able to move in every direction, including going sideways without turning (called strafing), and point turning;
- a Hokuyo UBG-04LX-F0 laser scanner [5] for mapping the environment (2);
- a lift mechanism (3) that allows the body of the robot to move up and forward at the same time, or down and backwards, for grabbing objects high and low;
- two Exact Dynamics iArms [6], on two mounting points on the left and right side of the robot (4), with each gripper having two fingers;

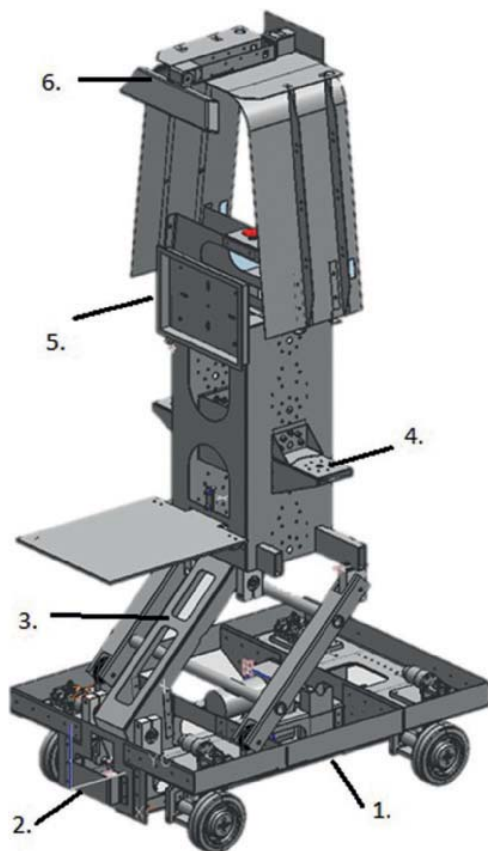


Table 3: ROSE dimensions

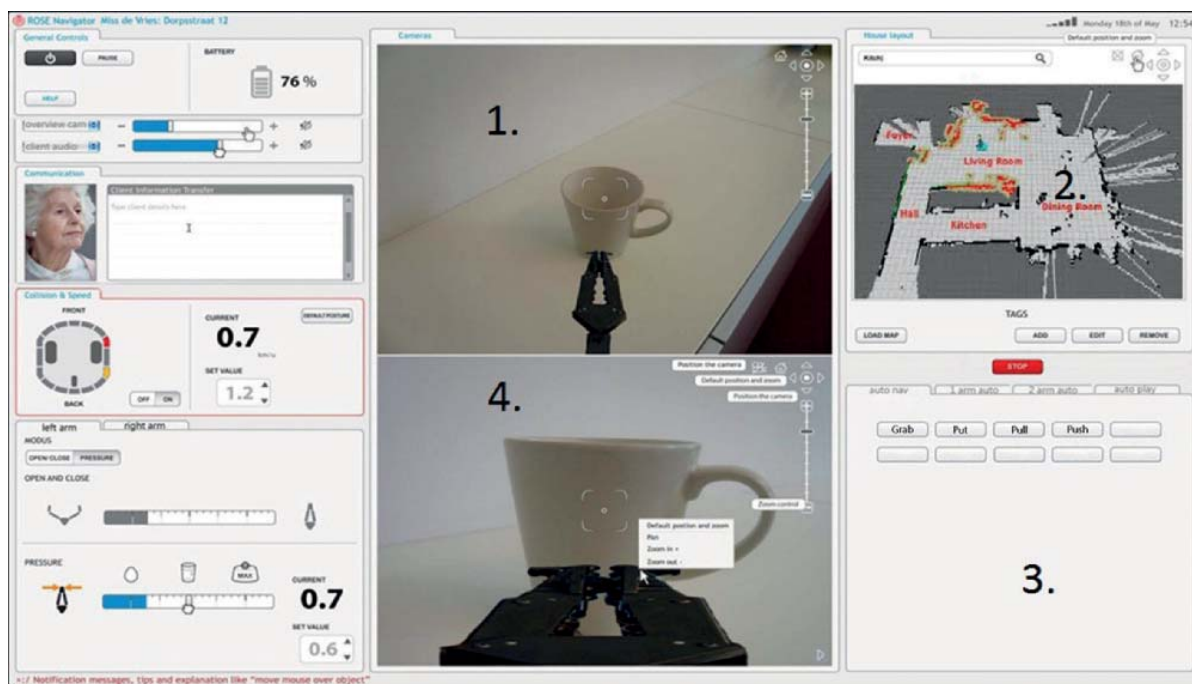
Height (lift down)	145 cm
Height (lift up)	170 cm
Width	60 cm
Length	80 cm
Weight	80 kg
Reach (height)	0-198 cm
Reach (front, from body)	60 cm
Reach (front, lift up, from body)	85 cm
Reach (side)	103 cm

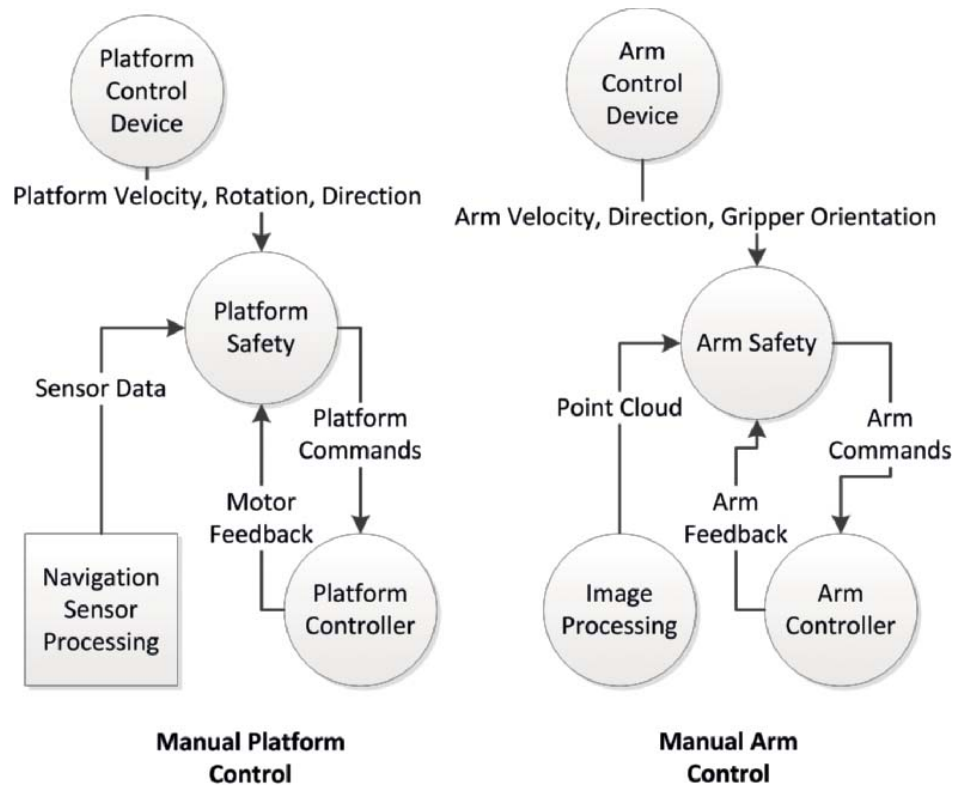
- a 10.1" TFT screen with microphone and speakers for audio/video communication between operator and client (5);
- an Xbox Kinect camera [7] for determining the coordinates of objects (6), which is mounted on a pan-tilt neck system, such that the camera can be turned left and right over 90°, turned up over 45°, and down over 90°;
- two eight-core I7 2.1Ghz computers with 4Gb RAM, one for navigation and path planning, and one for image processing and arm control;
- a Wi-Fi router for communication with the cockpit, locally or remotely via an access point to the internet.

2 Mechanical design of ROSE.
3 ROSE cockpit interface.

Cockpit design

The operator cockpit consists of a PC with a joystick (no force feedback) used for moving the robot, and a Space





4 ROSE manual control architecture.

Navigator [8] for manually controlling the arms. Furthermore, the cockpit is equipped with a headset and a webcam for communicating with the client.

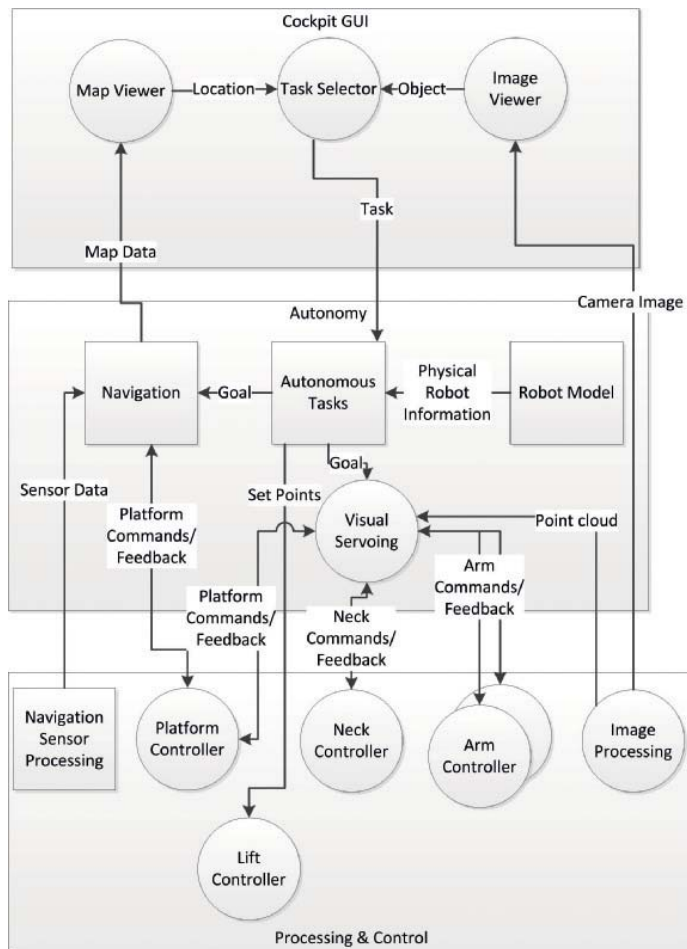
The user interface (see Figure 3) shows the 2D image of the Kinect camera (1). Operators can select different objects on the image and then select a command, for example ‘move’, ‘grab’, ‘place’ (3). The first time the robot explores its environment, it creates a 2D map (2). After that, the map is loaded from a file. Superimposed on the map is the information from the laser scanner, showing obstacles like tables, chairs and people. A footprint of the robot is also displayed on the map, displaying its current location and orientation. By clicking on a location in the map and selecting a ‘move’ command the robot computes a path to the desired location and autonomously moves to that location.

Below the image of the overview camera, space is reserved for the image of a second camera mounted in the gripper of an arm (4). This allows the operator to accurately position the gripper towards an object. Both arms can be equipped with a camera. However, the operator will only be controlling one arm at a time, switching between cameras.

Software architecture

Open-source ROS (Robot Operating System [9]) provides a middleware layer that allows communication between a set of executable software components (nodes). Nodes communicate with each other via either a remote procedure call, a publish-subscribe mechanism or a goal-feedback-result mechanism. ROS also provides nodes (e.g. for navigation). In our architecture, nodes are depicted by circles. For readability, groups of nodes are depicted by blocks if they have the same kind of logical structure (e.g. each autonomous task is implemented as a node), or if they work closely together (e.g. nodes used for navigation). Arrows describe the type of message sent from one node to another. For readability, we only depict the most relevant communication channels.

ROSE is either controlled manually or it performs autonomous tasks. Figure 4 shows the logical architecture for manually controlling the platform and an arm. The robot can be driven by a joystick. The Platform Control Device node reads input from a joystick. This input is sent to a Platform Safety node that checks whether it is safe to drive the robot, for example that no obstacle is in the way. Platform Safety receives sensor data from a laser range finder and ultrasound sensors. If it is safe to move, the



same nodes that are used for manual control. For readability, instead of showing two separate arrows, we use two-sided arrows to show that control nodes receive commands and send feedback. The operator uses a task selector in the GUI to select a task (like grab, open, put). Most of these tasks require selecting an object from the image window. One task, move to a location, requires a location selected on a map.

Autonomous tasks make use of the physical model of the robot and require that either the platform or the arms move to a location, for instance to grab an object. If the robot has to move to a location, a goal (destination) is sent to a group of nodes that jointly navigate to that location. These include nodes for path planning, localising the robot on the map, and different types of manoeuvring (e.g. long-distance navigation differs from positioning close to an object). After receiving the goal, the navigation nodes compute the path to it. First the path planner computes an overall path, which it breaks up in small sections. It then starts moving the robot by sending speed commands to the wheels. While moving, the path planner receives encoder data from the wheel motors, which is used to compute the distance and direction the robot has travelled to determine if it is still on its path. If not, the path planner computes a new path.

If the robot has to perform a task with its arms, a goal is sent to a Visual Servoing node. This node uses a point cloud to determine the location of the object on the screen selected by the operator and sends the proper commands to the arms to execute the task. Visual Servoing may also involve using the neck to track an object or gripper with the camera, or using the platform to perform complex tasks requiring simultaneous arm and platform movement.

Besides the control components, the robot also provides video communication with the client (not depicted). The operator can see the client via the Kinect camera. The client can see the operator via a webcam interface. Audio communication between operator and client is also provided. This interface is completely separate from any of the control components. Furthermore, the robot also provides feedback for the operator. A node keeps track of system status and displays information on the screen for the operator, such as which task is being executed and warning the operator when the robot is approaching an unsafe position (e.g. when it gets too close to a wall or table).

In our implementation we re-use several parts of an existing ROS software stack, including the navigation stack, laser, Kinect and Space Navigator nodes. However, we also developed several new nodes, such as our cockpit, neck control, iARM interfaces, tracking of the arm gripper with

Platform Controller is sent the desired velocity, direction (in case of strafing) and rotation (in case of turning), which it translates to motor commands. Manual control of an arm is very similar. The Arm Control Device node reads input from e.g. a Space Navigator. This input is sent to the Platform Safety node. Here safe also means that a number of criteria are met, such as the arm not colliding with an object or the robot itself. The Arm Safety node receives point clouds from the camera to determine safety. If the desired movement is safe, the velocity, direction (of moving the gripper) or orientation (for turning the gripper) are translated to arm commands for motor speeds or joint angles.

Figure 5 describes the logical architecture for performing tasks autonomously and by Visual Servoing. Visual Servoing means that the camera is used to monitor the movement of the arm and to correct the arm when it does not move to its desired position or an obstacle is in its way. The Platform Control node and Arm Control nodes are the

5 ROSE autonomous control architecture.

the overview camera, and performing autonomous tasks, and we implemented a new path planning algorithm. In order to guarantee proper communication between ROS nodes, we developed a component-based architecture in which we modelled the communication between nodes using the formal modelling language Petri Nets [10]. With our framework we can guarantee that a software component inside a network of software components (like ROS) can always finish executing its task [11]. This correctness criterion is achieved by construction and we can simulate and analyse the behaviour of the software with software tools like CPN tools [12]. Specifically we modelled and validated the remote procedure call, publish-subscribe mechanism, and goal-feedback-result mechanism of ROS [13].

Evaluation

ROSE was extensively tested in a real-life apartment. After each session the operators were interviewed. Lessons learned:

- Controlling the robot manually is hard and it is hard for the operators to see what the robot is doing. It may be better to restrict the possibilities of driving manually or group them in modes.
- Grasping objects is considered easy, but there are still many limitations as to the objects that can be grasped. We need to improve both hardware and software to be able for the robot to grasp more objects. The operators find the robot performs tasks too slowly, but is able to perform tasks very precisely (e.g. grabbing a cup).
- Operating the robot from a distance using an optic fibre cable does not cause any delay. The bottleneck is the wireless connection inside the house.
- Because the client does not see what the operator is doing, it looks like the robot is even slower than from the operator's perspective. The operator has to become faster and the robot or operator has to show the client what he is doing to reduce perceived idle time.

The clients were also interviewed. They expect the robot could be very useful to them and make them feel safer. They are not worried about privacy and are not afraid of the robot. However, robot care should not completely replace human care in the future.

Acknowledgements

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IMPROVED GRASP ROBUSTNESS THROUGH VARIABLE TRANSMISSION RATIOS

Robotic hands should be robust, light and able to pick up various objects. Underactuated hands (with less actuators than degrees of freedom) are very promising, because they show adaptive behaviour resulting in the ability to pick up different objects. Underactuated hands can use an enveloping grasp (also called power grasp) or a precision grasp (fingertip contact only). Two methods to improve grasp robustness are described: 1) improving precision grasp robustness, and 2) converting from precision to power grasp.

STEFAN SPANJER

Underactuation has been utilised extensively in the design of robotic hands in order to allow for multi-DoF (degree of freedom), yet lightweight and compact systems [1]. Benefits of this approach include passive adaptability to a wide range of object sizes and shapes, lower contact forces during object acquisition, mechanical simplicity and durability, and lack of need for complex sensing and control. However, one of the disadvantages of the approach comes during precision grasping, where unconstrained DoFs can cause the mechanisms to reconfigure and potentially lose the grasp. Power grasps, where the hand envelops the object, are more robust than precision grasps, where the object is grasped between the tips of the fingers. Precision grasps are necessary when objects are small or when objects are approached from above.

For any grasp type, robustness is an important aspect. Here, robustness is defined as the ability to resist external forces. There are several factors that influence the robustness of an underactuated finger's precision grasp, including the object-finger contact location, the friction parameters, the

finger configuration, and the mechanism design parameters.

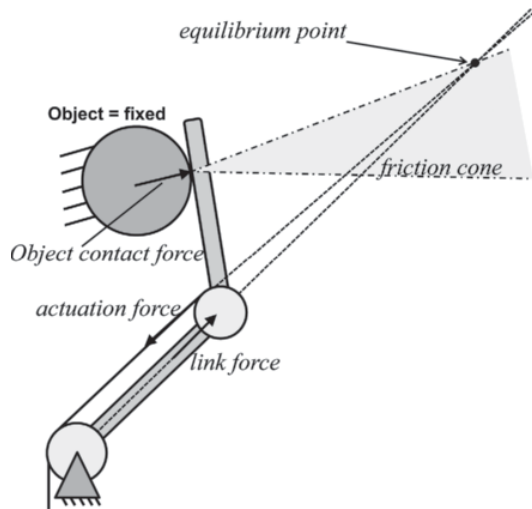
In case of a precision grasp, equilibrium occurs when the 'equilibrium point' of the finger's distal link is contained within or on the edge of the friction cone (Figure 1). The equilibrium point is the intersection of the tendon line and the proximal phalanx line. There is equilibrium if the contact force points at the equilibrium point, because equilibrium of three forces is only possible when these forces intersect at one point. Otherwise the finger slides along the object. The sliding direction and rotation of the distal phalanx on the object can be easily verified with the use of the equilibrium point. If the contact force produces a clockwise moment around the equilibrium point, then the distal phalanx will rotate clockwise and vice versa. The sliding will result in a precision grasp, power grasp or contact loss of the object.

A 2D mathematical model was made of a finger with two phalanges and a fixed object. This model predicts if and how the finger slides along the object and whether

AUTHOR'S NOTE

Stefan Spanjer obtained his M.Sc. in Mechanical Engineering at the University of Twente, Enschede, the Netherlands. He was awarded the 2012 Wim van der Hoek Constructors Award for his M.Sc. thesis on a design for a robot hand, in particular the finger controls. Currently, he is the CEO of start-up company KITE Robotics, which develops autonomous window cleaning robots.

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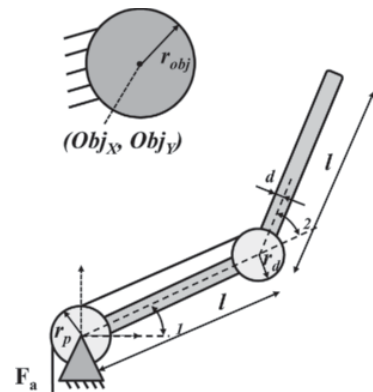
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equilibrium is reached. Quasi-static conditions and equal coefficients of static and kinetic friction were assumed. The finger is actuated by a tendon with force F_a and the finger has pulleys with radii r_p and r_d and angular spring stiffnesses K_p and K_d at the proximal and distal joint, respectively (Figure 2). Both links have length L and width d ; the proximal link is rotated over angle θ_1 with respect to the horizontal. The distal link is rotated over angle θ_2 with respect to the proximal link. In the analysis, the finger contacts a fixed circular object at position (Obj_x, Obj_y) with radius r_{obj} . More detailed information on the model can be found in [2].

Robustness improvement of precision grasp

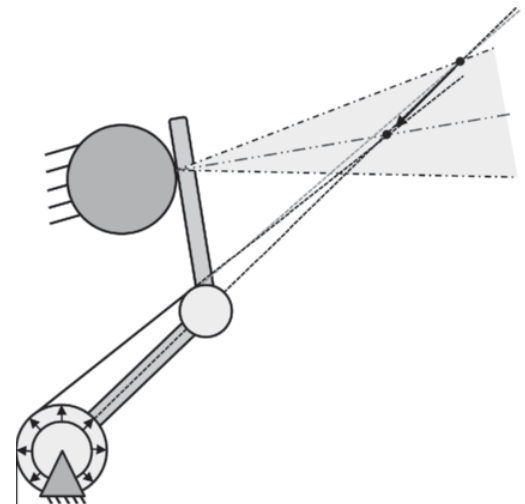
Principle

Often the distal phalanx slides along the object before equilibrium is reached in case of a precision grasp. In that case, the equilibrium point is located on the edge of the friction cone (Figure 1). This is simulated with the model. Due to a maximised friction force, the achieved state of equilibrium is not very robust. Even a small disturbance force pointing in the opposite direction of the friction force is enough to break equilibrium. The robustness can be improved by repositioning the equilibrium point in the friction cone (Figure 3). By changing the radius of the proximal pulley after grasping, the equilibrium point can be controllably shifted from the edge of the friction cone to the centre of the cone. By doing so, the robustness against random force disturbances is maximised and the required friction force in the newly established configuration goes to zero.



2

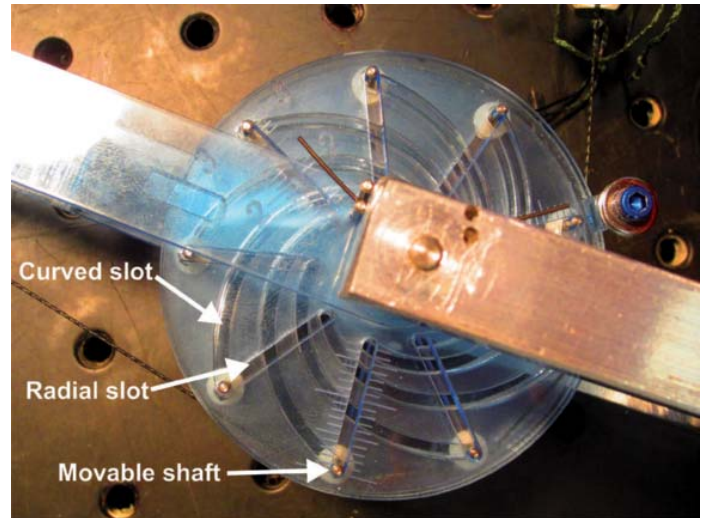
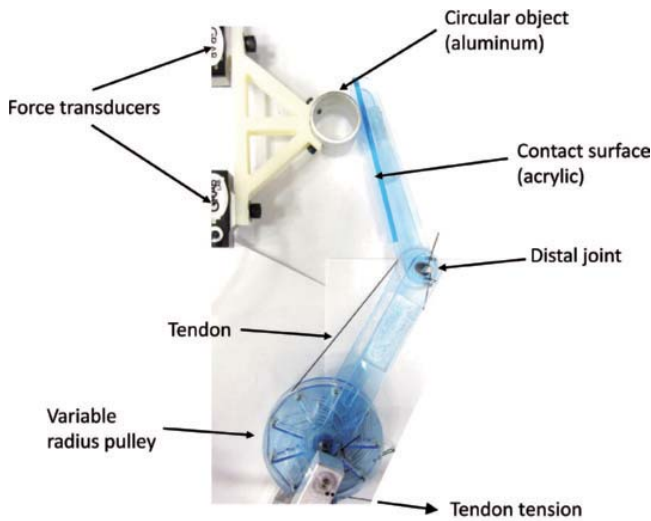
- 1 The equilibrium point is the intersection of the force lines of the actuation and link force.
- 2 Various parameters of the finger model.
- 3 Relocation of the equilibrium point in the centre of the friction cone by changing the transmission ratio.



3

Validation

In order to evaluate this concept in a real-world scenario, an experimental set-up was developed for actively changing the transmission ratio ($= r_p/r_d$) and simultaneously measuring the contact forces on a target object. With this set-up, it can be verified that the friction force at the contact location decreases towards zero when the radius of the proximal pulley is changed to move the equilibrium point towards the centre of the friction cone. Figure 4 shows the set-up of the experiment, including an acrylic finger with music-wire springs and low-friction joints, a small cylindrical object mounted on a 2-DoF force-sensing platform (using two 1-DoF load cells, Transducer Techniques MLP-10), and a torque-controlled motor (maxon F2140) applying the tendon-based actuation.

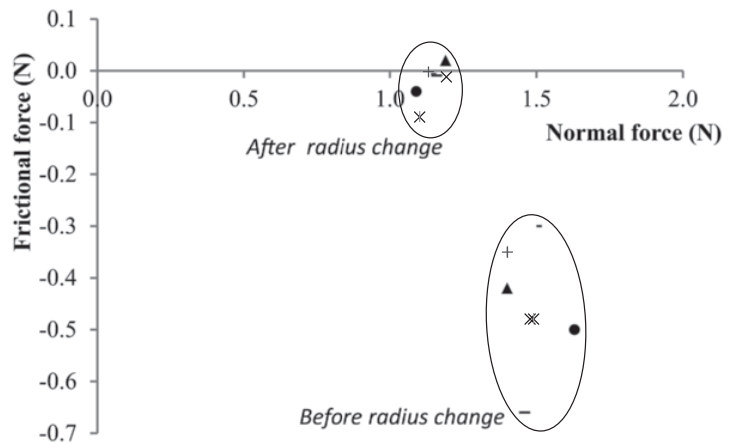


The proximal pulley employs a mechanism that allows the effective radius to be changed by rotating a top and bottom plate with respect to one another (Figure 5). Shafts around which the tendon is routed (i.e. the effective pulley), are located between the straight slots in the bottom plate and the curved slots in the top plate. As the plates rotate with respect to one another, the shafts move radially, changing the effective pulley radius. Small pulleys are mounted on the shafts. The logarithmic spiral slots are designed to have a relatively large angle with the radial slots in order to reduce friction and allow smooth movement of the pins. The whole system is connected to the proximal shaft with bearings, so it can rotate freely.

The experiment was executed as follows. The finger is initially at rest, with angles $\theta_{1,ini}$ and $\theta_{2,ini}$, and the actuation force F_a is smoothly increased to 12 N. During this motion, the finger makes contact with the object and slides until the equilibrium point reaches the edge of the friction cone, after which no additional movement can occur. Next, the angles θ_1 and θ_2 are measured and the contact and friction force are calculated from the sensors. With this data the required radius change is calculated as follows:

$$\Delta r_p = \left(\frac{d}{a} L \cos \theta_2 + L \sin \theta_2 \right) \frac{F_t}{F_a}$$

Here a is the contact position on the distal phalanx and F_t is the friction force between object and distal phalanx. The proximal pulley radius is changed manually to the desired new radius, and the contact and friction force are measured again. During the radius change it is ensured that no contact/kinematic changes occur.

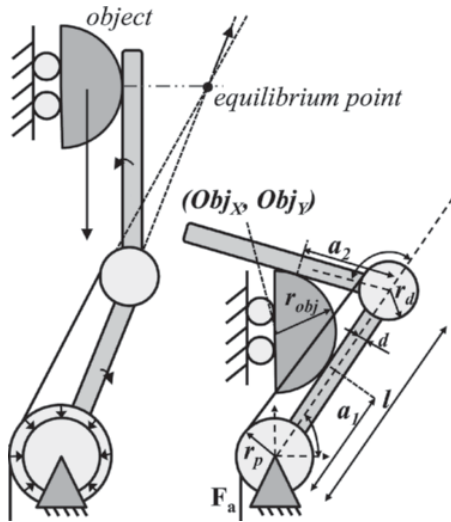


4 Experimental set-up for model validation.

5 Variable radius mechanism.

6 Contact forces before and after proximal radius change.

Figure 6 shows the results from this study. The normal contact force F_n is presented on the x-axis and the tangential friction force on the y-axis. Each symbol type represents a different trial; for each trial the object position and radius are the same. The points clustered in the lower right part of the figure are the measured forces before the radius has been changed, while the points on the upper part of the figure represent the forces after the radius has been changed. From Figure 6 it is clear that the friction force decreased towards zero when the radius was changed. Since the contact location did not change, this result indicates that it is possible to successfully move the equilibrium point into the centre of the friction cone, thereby increasing the



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amount of allowable disturbance force before the grasp is destabilised. It was also interesting to change the radius more than one should; for a larger radius change the friction force increased again in the opposite direction.

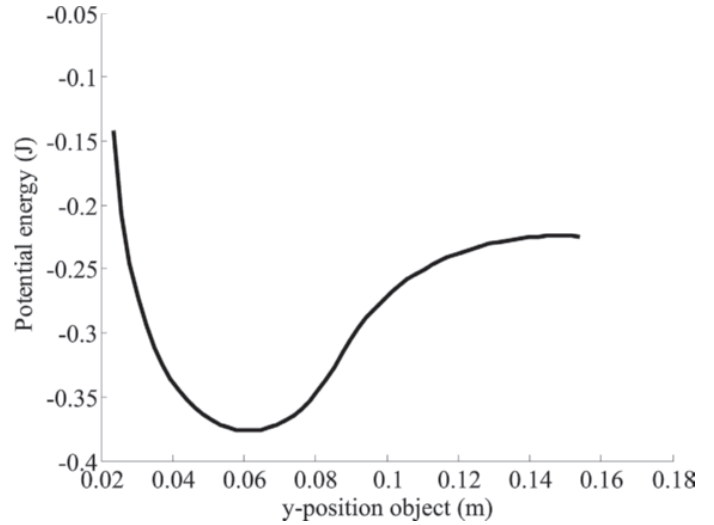
The variable transmission ratio maximizes the robustness; the allowable disturbance force is increased from 0 to $\mu \cdot F_n$, where μ is the coefficient of friction. The normal contact force is linearly related to the actuation force, so the allowable disturbance force can be higher when the actuation force is increased.

Convert from precision to power

Even more robustness

The previous section covered improving the robustness of the precision grasp by actively varying the transmission ratio of an underactuated finger after an object is grasped. The transmission ratio is changed such that the required friction force between finger and object is reduced to zero. This way, the equilibrium margin for unknown disturbances is maximised. Still, for high accelerations of hand and object, the power grasp is preferred because of its greater robustness. Ideally, a hand should be able to convert from precision grasp to power grasp after an object has been grasped, because then both small and large objects can be picked up and the desired robustness can be realised.

This is achieved by varying the transmission ratio in an underactuated finger after an object is grasped, which leads to motion of the finger and object. The principle of the variable transmission ratio is the same as described before,



8

7 Transition from precision to power grasp.

8 Potential energy curve for a proximal radius of 30 mm.

but now this ratio is changed in order to break equilibrium and move the object into the hand; by changing the radius of the proximal pulley the equilibrium point can be controllably shifted outwards. As a consequence, the distal link rotates counterclockwise and brings the object into the palm of the hand until equilibrium is reached again (Figure 7). For simplicity, symmetry is assumed between the two fingers that hold the object. The object is able to move freely in the y-direction while the x-direction is prohibited.

Model including potential energy

The model is very similar to the model described in previous sections, but now friction is not included. The principle of potential energy is used to estimate stable and unstable positions of the object in the hand.

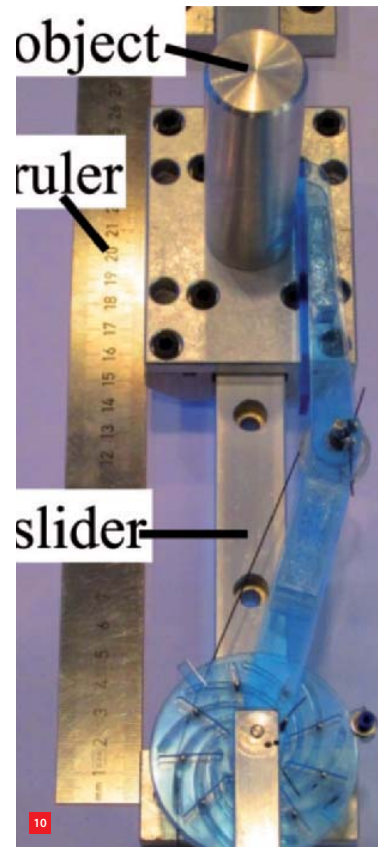
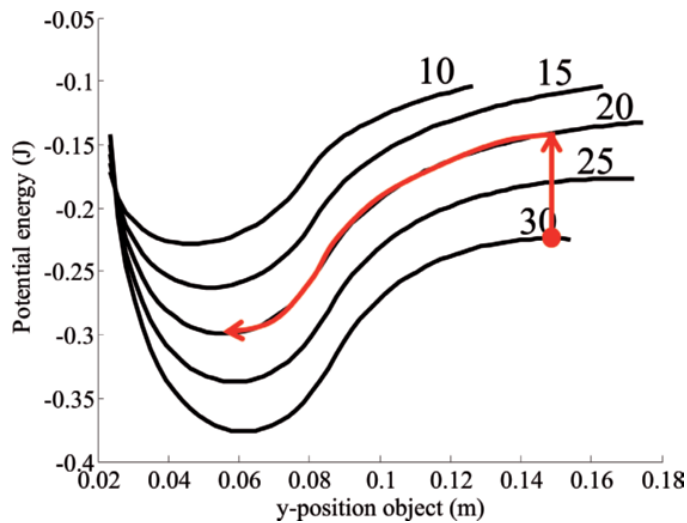
In the model the object is fixed; for different fixed positions the equilibrium of the finger is calculated. Everytime the potential energy is also calculated:

$$E_p = F_a \Delta h + \frac{1}{2} K_p (\theta_1 - \theta_{1,ini})^2 + \frac{1}{2} K_d (\theta_2 - \theta_{2,ini})^2$$

The total actuation force F_a is considered constant for different positions. $\theta_{1,ini}$ and $\theta_{2,ini}$ are the rest position angles at the proximal and distal joint respectively; at this position the torsion springs perform no work. Δh is the change in tendon length:

$$\Delta h = r_p (\theta_1 - \theta_{1,ini}) + r_d (\theta_2 - \theta_{2,ini})$$

For different y-positions of the object the potential energy is calculated. The potential energy can be displayed as a function of the y-position of the object, see Figure 8.



The gradient of the potential energy is equal to the resultant force on the object. So, when the gradient is zero, the resultant force is zero. Therefore, these points are the positions of the object where the object and finger are in equilibrium in case the object is not fixed.

9 Potential energy curves for different radii (mm).
10 Experimental set-up for validating the conversion from precision to power grasp.

Figure 8 shows two points where the gradient is equal to zero: a minimum and a local maximum. The stable minimum is the position of the object when finger and object are in power grasp mode. Small disturbances will lead to other positions, but the object will return to the point with minimum energy. The same curve shows also an unstable maximum at $y = 0.15$ m. Then the finger and object are in precision grasp mode. In this case only the distal phalanx has contact with the object and the contact force does not have a component in the y -direction. Different energy curves can be obtained for different radii of the proximal pulley, see Figure 9.

When the finger is in precision grasp mode and the radius is changed, the derivative at $y = 0.15$ m deviates from zero, which means a force develops that tends to move the object. Decreasing the radius results in a more distal location of the equilibrium point. As a result, the distal phalanx rotates into a power grasp, as indicated by the red lines in Figure 9.

Experimental validation

An experiment was set up to verify that the finger and object can convert from precision to power grasp by changing the transmission ratio. The experiment was also used to validate the end position of the object, which is equal to the position of the minimum of the potential energy curve. The parameters are the same as in the model,

only the joint stiffnesses are different: $K_p = 0.015$ Nm and $K_d = 0.048$ Nm. The set-up of the experiment is shown in Figure 10. The same acrylic finger is used as in the experiment described before. The constant actuation force is supplied by a 1kg weight. The object is mounted on a linear guide and, therefore, is able to move freely in the y -direction.

The start position of the finger in the experiment is the precision mode: the finger touches the object by the distal link and is in an equilibrium state (red dot in Figure 9). The y -position of the object depends on the radius of the proximal pulley, so that the object is located at the level of the equilibrium point. In the next step the radius is lowered until the object starts to move. The end position of the object will be compared with the expected minimum of the energy curve of that radius.

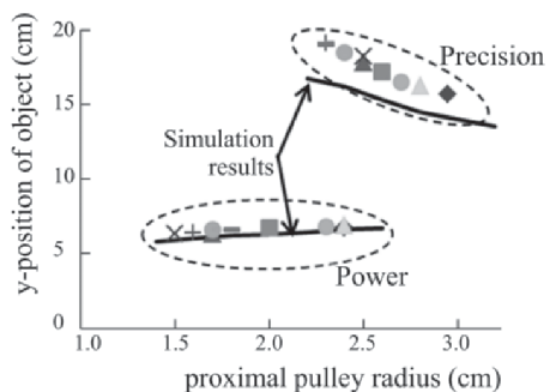
From the experiment it is clear that the object moves to the proximal phalanx. Figure 11 shows different trials of the experiment. The start and end positions of the object together with the start and end radii of the proximal pulley are depicted. The expected start and end positions from the simulation results are also shown.

In Figure 11 the differences between simulation and experiment in precision grasp (average of 19 mm) are larger than the differences for power grasp (average of 3.4 mm) for a finger with a link length of 100 mm and an object with a radius of 15 mm. This is probably due to friction between finger and object, which is not modeled and has more influence in a precision grasp.

In finger-object interaction without friction, the equilibrium of the precision grasp is lost for an infinitesimal small proximal radius change. When friction is included, the equilibrium point has to be shifted outside the friction cone. The required radius change to convert from precision to power grasp increases for a larger coefficient of friction between finger and object. More information can be found in [3].

Conclusion

This study describes two different methods for improving grasp robustness. Both make use of a variable transmission ratio. In the first method the robustness is increased by relocating the equilibrium point into the centre of the friction cone by applying a variable transmission ratio between the proximal and distal phalanx. It maximises the robustness, with the allowable disturbance force increasing from 0 to $\mu \cdot F_n$. In the second method the robustness is increased even more, by converting from precision to power grasp. Again the transmission ratio is changed, but now in order to shift the equilibrium point outwards and break equilibrium. The distal phalanx then moves the object to the palm of the hand.



11

Acknowledgment

This research was only possible with the enthusiastic support of Prof. Just Herder from the Laboratory of Mechanical Automation (WA), University of Twente, Prof. Ravi Balasubramanian from the Robotics and Human Control Systems Lab, Oregon State University, and Prof. Aaron Dollar from the GrabLab, Yale University.

11 Experimental results (measurements are very similar to simulation results).

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Miniature Linear DC-Servomotors

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CHANGING THE FUTURE OF INDUSTRIAL ROBOTS



(Source: INCAS³)

The European manufacturing production industry is steadily becoming more focused on higher added value production, requiring companies to be both lean and flexible in order to survive in the current competitive market. Smart industrial robots are needed in order to make this possible. These robots are equipped with multiple sensors and can operate autonomously on several complex tasks. They are a key success factor for industrial companies.

JAN REINDER FRANSENS AND MAARTEN ESSERS

Introducing: SmartBot

Intelligent, autonomous, sensing robots and vehicles are becoming more and more common in automation paradigms worldwide. In addition to the more common industrial automation, agriculture and maritime autonomous solutions are rapidly emerging. These three areas are combined in the SmartBot project: a cross-border collaboration between a number of partners from Germany and the Netherlands. The SmartBot project consists of three sub-projects, aimed at the application of intelligent robotics in the shipping industry (RoboShip), agriculture (AgroBot) and the manufacturing industry (SInBot). Together, these projects aim to improve efficiency and effectiveness in their respective fields, in order to stimulate European businesses and reinstate internationally outsourced jobs.

SInBot

In particular, SInBot is aiming to reinstate manufacturing employment for small and medium-sized enterprises by improving the efficiency of industrial robots in performing small to medium-sized production runs. Nowadays, industrial robots are used mainly for repetitive work on large series (i.e. mass production). They perform their tasks efficiently, are cost-effective and moderately accurate. However, they have a long reconfiguration time, lack task flexibility as well as absolute accuracy. To improve the efficiency of these robots, SInBot plans to equip them with multiple sensors and let both robots and sensor networks

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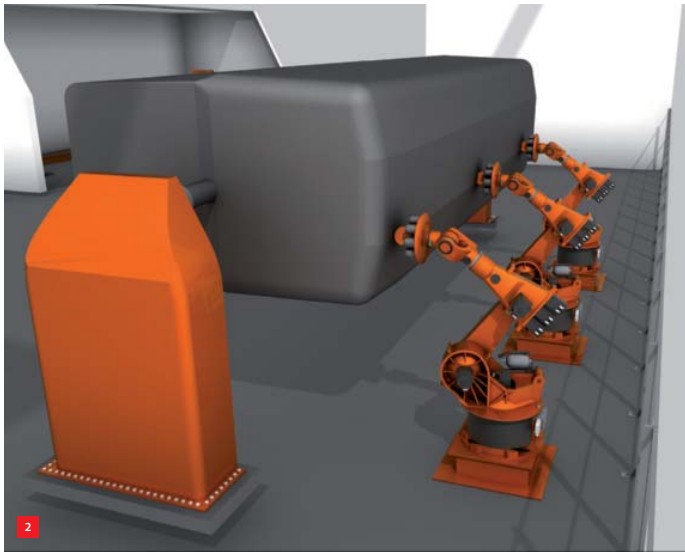
communicate using a flexible ICT infrastructure enabling autonomous operation while performing complex tasks.

The tipper case

Project SInBot was proposed, in part, due to a burning question in the transportation sector. For example, Luinstra, a transportation and logistics solution company from Nieuwleusen, the Netherlands, is planning to manufacture fiber-reinforced polymer (FRP) lightweight tippers (dump truck beds; see Figure 1) in a mass-customisation setting. The manufacturing of these tippers is costly if done by hand and is therefore not economically feasible for European production.



1 Luinstra's FRP-tipper provides a case for smart robotisation. (Source: www.composittransport.com)



Objectives

As a partial result from the Luinstra case, the main SInBot objective is to develop industrial robots which are flexible, can work autonomously and are accurate without relying on the extended learning cycle associated with industrial robot work preparation. The robots should be able to cooperate and distribute the production tasks amongst one another. The system should be easily extendible to other robots (for example, automated guided vehicles (AGVs), industrial robots, or automated machinery) to increase the output, with more (or other) sensors to increase accuracy. Finally, the framework should be open, i.e. it should be possible to extend it with hardware from different suppliers.

Approach

A number of parties (see box) are working together on the SInBot project to realise the aforementioned objectives. In this team, the academic partners focus on the algorithms and software structure needed to realise, among others, the cooperation between the robots and the translation from CAD data to actual production tasks. The industrial partners contribute their extensive knowledge of industrial production systems and environments.

This combination of academic and industrial partners has resulted in the realisation of several demonstrators and virtual simulations to prove the feasibility of the SInBot concepts in a real production environment.

Challenges

The realisation of the SInBot objective is not straightforward; there are a number of challenges. Not only should the system work in a clean environment, but also in harsh production settings. The robots in the system should be able to work together, for example the robots decide which robot will perform which task, they can help one another, and should be able to stop working mid-task, for later completion by another robot. Therefore, the system should be flexible in task acceptance. For example, reconfiguration of manufacturing settings should be automated and fast. Finally, the system should be robust. If a sensor or even a robot breaks down, production should proceed normally, if possible.

To realise these tasks, a common framework will be used to translate CAD data to tasks for the available robots, keep track of the capabilities of the available machinery, create production tasks, divide these tasks using an auction model (which robot is doing what?), monitor these tasks and organise the communication between the different hardware components of the system. At the base of this common framework is a Data Distribution Service (DDS), used to keep track of all communication between the above mentioned tasks and the hardware.

Luinstra is looking for ways to improve the efficiency of industrial robots working on large composite products. Since each unique tipper could be produced in series as small as ten, the robots should be flexible in task acceptance. Manufacturing large products requires long stretches of industrial robots, which further diminishes the feasibility of mass-customisation of FRP-tippers. Therefore, the needs of this company include task flexibility to improve efficiency in work preparation, as well as negligible reconfiguration times to decrease the amount of required industrial robots, the introduction of robot-robot and robot-human cooperation, and dynamic task reassignments to counter robot failure; see Figure 2.

2 Manufacturing large products in a mass-customisation setting poses challenges to the deployment of industrial robots. (Source: STODT)

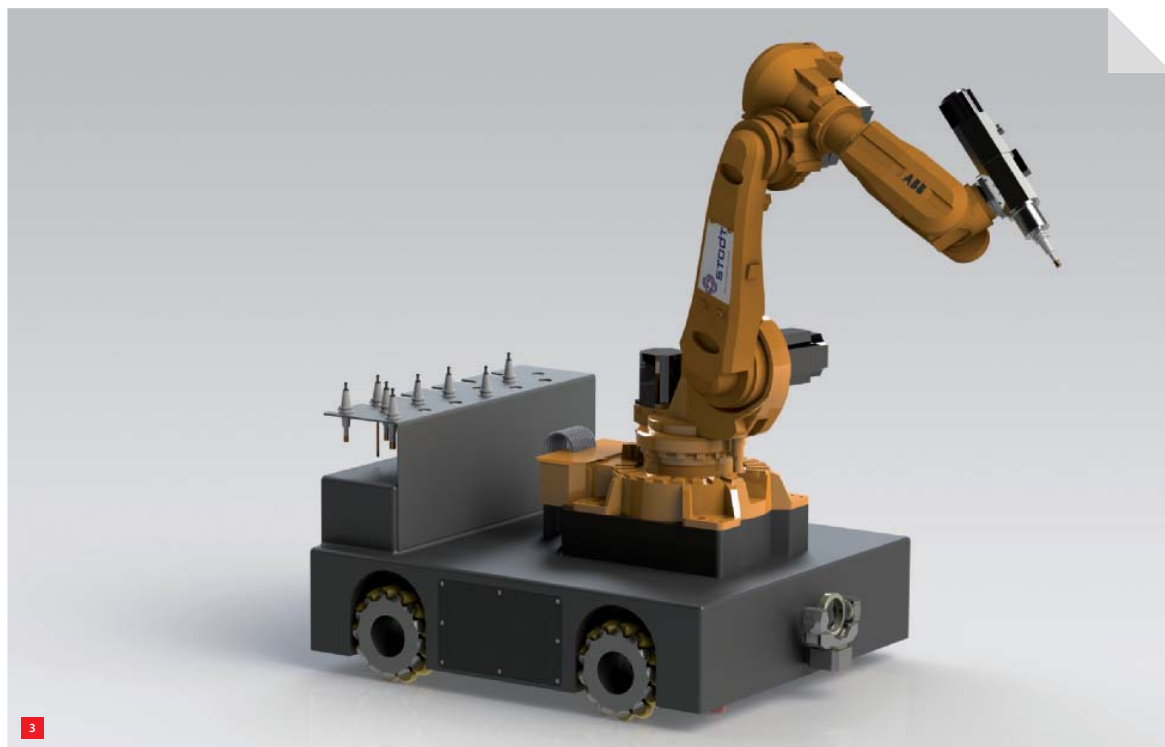
SInBot partners

Dutch:

- INCAS³ (Assen)
- Irmato (Drachten)
- Luinstra Bronbemaling (Nieuwleusen)
- University of Groningen, Faculty of Mathematics and Natural Sciences (Groningen)
- STODT Toekomsttechniek (Hengelo)
- University of Twente, Faculty of Engineering Technology (Enschede)
- Xsens

German:

- Haake Technik (Vreden)
- Grunewald (Bocholt)
- Westphalian University of Applied Sciences (Gelsenkirchen)



3 For enhanced task flexibility, a robot can be mounted on an automated guided vehicle. (Source: STODT)

To achieve the required task flexibility, the robots will be positioned on the desired production site by AGVs; see Figure 3. A combination of different sensors is used to position these AGVs. By using these partially redundant sensor systems, robustness and accuracy can be guaranteed even if a sensor is damaged or its accuracy is limited due to environmental conditions. If large production parts need to be moved, multiple robots should be able to work together. Coordinated motion (i.e. moving in formation) is required to perform this type of task. Robust algorithms will be developed that are capable of functioning properly even if sensor accuracy is limited.

Obtaining the required absolute accuracy is probably one of the biggest challenges associated with this project. The absolute accuracy of industrial robots is not always adequate to obtain the required process accuracy. This is not a problem in mass production because a long robot learning and reconfiguration cycle is allowed. However, this approach is not economically feasible for small series. Therefore, SInBot is looking for a way to correct the tool trajectory online. This requires fast and accurate (tolerances less than ± 0.1 mm) sensor systems that communicate directly with the industrial robot controller, and can rapidly correct tool speed and direction. Multiple robots will be in use in the production plant of the future. These robots will cooperate and interact with humans. Thus, the robots

should be able to work safely in an environment with moving (and fixed) obstacles. A combination of sensors, software and hardware must guarantee a fail-safe system.

Conclusion

SInBot is a significant research project with challenging objectives. Much work still has to be done, but the big picture has become more focused. The system architecture has been defined and a number of small demonstrators are already operational in the laboratories. The next steps will include the integration of multiple sensors, the demonstrators, and the software framework. At the conclusion of the project in December 2014, SInBot aims to prove the feasibility of mobile, (task-)flexible, accurate and robust robot manufacturing systems; the future of industrial robots is about to become much clearer. ■

INFORMATION

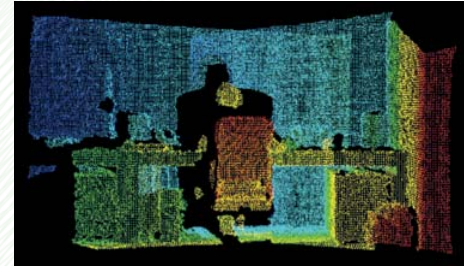
Smartbot is supported by the Interreg IVA programme Deutschland-Nederland.

WWW.SMARTBOT.EU

WWW.DEUTSCHLAND-NEDERLAND.EU

FOCUS ON IMAGE SENSORS

Robots need sensors to operate properly. Using a single image sensor, various aspects of a robot operating in its environment can be measured or monitored. Over the past few years, image sensors have improved a lot: frame rate and resolution have increased, while prices have fallen. As a result, data output has increased and in a number of applications data transfer to a processing unit has become the limiting factor for performance. Local processing in the sensor is one way of reducing data transfer. A report on the Vision in Robotics and Mechatronics project.



JAAP VAN DE LOOSDRECHT, JOHAN VAN ALTHUIS, JOS GUNSING, DANIEL TELGEN, MARK STAPPERS AND PETER KLIJN

Vision in Robotics and Mechatronics was a so-called 'RAAK' project (Regional Attention and Action for Knowledge circulation); last month the concluding symposium was held. It focused on applications of vision techniques in the field of robotics and mechatronics. The project had a number of different goals. As a first step, a vision application was chosen in which data transfer limits performance. This served as a case study of local processing as a means to reduce data. The possibilities of OpenCV (open-source computer vision software library) and the Point Cloud Library were investigated for further processing of the reduced data. The items investigated were implemented in a number of demonstrators.

Applications

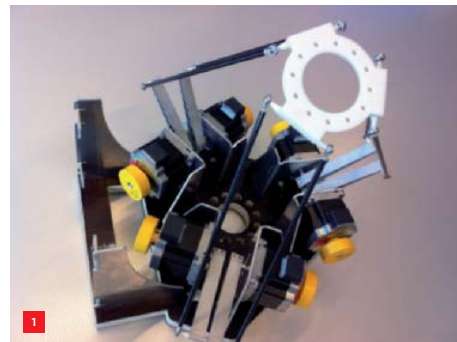
The Mechatronics department at Fontys (see the box on the next page for all project partners) is collaborating with TU/e to develop a robot for home care. This robot must be able to move around autonomously in different environments. A 3D sensor can be used so that the robot can avoid colliding into objects in that environment. Light conditions may vary a lot in this application. In terms of autonomy, power consumption is also a cause for concern.

Mechatronics researchers at Avans are focusing on gripper technology. A 3D sensor is considered a useful sensor for grippers. It can recognise an object and determine the distance between object and sensor, and the moment when the object is within grasp. Such a sensor should be small and have an interface that does not require many connections and that secures reliable data transfer.

The HU department of Micro Systems Technology/ Embedded Systems is working on improving Agile

Manufacturing methods. Agile Manufacturing uses production equipment with downloadable functions. The functions of production equipment can be changed during production, resulting in a more efficient use of equipment. HU is developing a relatively cheap and modularly built pick & place robot, the HUniplacer (Figure 1). This HUniplacer will be used for research into reconfigurable machines, ROS (Robot Operating System), intelligent agents and computer vision.

1 The HUniplacer is a delta robot.



AUTHORS' NOTE

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Stappers is a researcher at Fontys University of Applied Sciences for Engineering in Eindhoven, the Netherlands. Peter Klijn is a lecturer and researcher at the Academy for Engineering and Informatics of Avans, and a member of the Mechatronics research group at Avans.

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A configurable vision sensor compatible with ROS is the perfect solution for Agile Manufacturing. Based on the requirements, it was decided to apply a sensor that can be used as a 3D sensor as well as a 2D sensor. The sensor should be able to generate depth maps as well as (processed) 2D images.

The HUNiplacer requires the highest frame rate of the three applications described. A frame rate of 50 fps (frames per second) is sufficient for this application. The vision system must be able to work under widely varying light conditions (indoor as well as outdoor, even in direct sunlight). Power consumption must be minimised. For the further processing of 3D images, NHL investigated the Point Cloud Library. TU/e contributed with overall support on the theory of image processing and its implementation.

3D vision techniques

Overall, there are four techniques to generate a 3D image using vision sensors.

Structured light

A source projects a light pattern onto a surface. The image of the pattern is recorded with a 2D sensor. This image is compared to a reference pattern. From the differences between the reference pattern and the recorded pattern, a depth map can be calculated. A well-known sensor that uses this technique is the Microsoft Kinect sensor. It uses an infrared (IR) source and sensor to generate the depth map. It also has an RGB image sensor (for colour detection: Red, Green, Blue). Images have a resolution of 640x480 pixels, at a frame rate up to 30 fps. The sensor has a range of 0.6 to 6 m. Accuracy depends on distance to the object. At 1 m, it is in the order of magnitude of a few mm. As they operate with IR light, the sensors do not work in direct sunlight.

Scanning-based

This technique uses the same principle as the structured-light approach. A source of light projects a spot or a sheet of

light onto a surface. A 2D image sensor records the spot or sheet of light and compares it to the image on a reference plane. From the differences between these two images, the distance can be calculated (for example, using triangulation). With a spot or a sheet of light, you only get a 1D or 2D image. A scanning movement in one or two directions must be added to get a 3D image. Accuracy, range and reliability depend on the system's set-up.

Time of flight (TOF)

A TOF camera calculates distance by measuring the time of flight of a light signal. The camera transmits a light signal and records the reflected light. The time between transmission and reception of the light is used to calculate the distance of an object. Two approaches can be distinguished: 'range-gated' and Photonic Mixer Devices (PMD). In the first case, short light pulses are emitted and the total amount of light transmitted and received is measured. PMDs generate a sine in the RF range (radio frequency) and measure the phase difference between the transmitted and the received wave. The MESA SwissRanger 4000 is an example of a PMD. It has 176x144 pixels and a maximum frame rate of 50 fps. Accuracy is approximately 10 mm and range at this accuracy is 0.8 to 5 m.

Stereovision

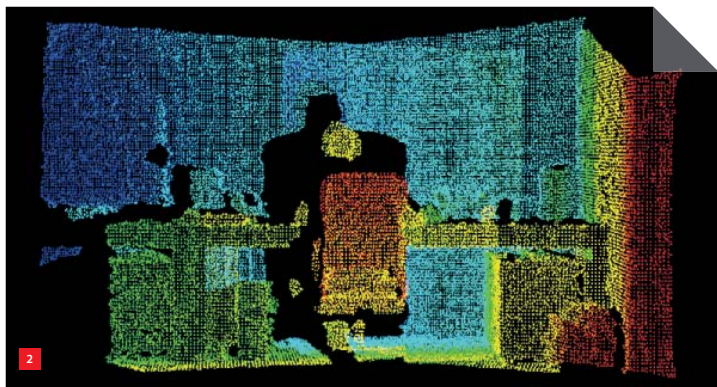
Stereovision uses two 2D image sensors that are placed a distance apart. A point of an object will have a certain location in the image of both sensors. The distance z can be calculated from the difference in location of the point in the two images:

$$z = \frac{f \cdot b}{d}$$

Here f is the focal length of the lens, b (baseline) is the distance between the two image sensors, and d the so-called disparity, i.e. the difference in position of the same object point in the two images. The sensors record a large number of object points simultaneously, of course. Therefore, it is possible to generate a 3D image for the field of view that the two sensors share. Accuracy and reliability of such a system depend on the image sensor, lens quality and baseline as well as the object and its environment. The frame rate depends on the camera/image sensor and processing unit used, as well as the data transfer rate. Stereovision algorithms are available for CPUs. The frame rate, however, is restricted by the data transfer between the camera and the processing unit. This could be resolved by implementing the stereovision algorithm in an FPGA (Field Programmable Gate Array, programmable electronics that can have parallel communication with a camera).

Participants in the project

- NHL Centre of Expertise in Computer Vision.
- Fontys University of Applied Sciences for Engineering, Mechatronics research department.
- University of Applied Sciences Utrecht (HU), department of Micro Systems Technology/Embedded Systems.
- Eindhoven University of Technology (TU/e).
- Academy for Engineering and Informatics at Avans University of Applied Sciences, Mechatronics research department.



2 Example of a point cloud.

Choice of sensors

It was decided to develop a vision system that uses stereovision and an FPGA to locally process the data. This decision was made because of the required frame rate, the desire to minimise power consumption, the varying light conditions, and the desire to have 2D and 3D images. To investigate the possibilities of the Point Cloud Library (PCL, see below), a Kinect sensor was used. By using this off-the-shelf sensor, it was possible to do the PCL work in parallel with the actual development of the vision system. This is why commercially available camera systems are also used in the demonstrators.

Division of work

The project was divided into different chunks of work, assigned to the various parties.

Stereovision system

- | | |
|--|------------------|
| • Hardware selection and design | Avans and Fontys |
| • Hardware implementation (VHDL in FPGA) | Avans |
| • Software development/test set-up | Avans |

3D data-processing software

- | | |
|-----------------------|-----|
| • Point Cloud Library | NHL |
|-----------------------|-----|

Demonstrators

- | | |
|---|-------|
| • Jenga robot | Avans |
| • HUniplacer | HU |
| • Localising objects using fiducials & QR codes | HU |
| • Object recognition | HU |
| • 3D images | HU |

Stereovision

A stereovision system is being developed. Signal processing will be done using an FPGA and PC. RGB cameras will be used that have VGA resolution (Video Graphics Array).

These cameras are equipped with a global shutter. The global shutter will be used to synchronise the different cameras. It will be possible to connect four of these cameras to the system. It will also be possible to use cameras with a rolling shutter. The system will also allow for four of those cameras to be connected.

The research system set-up is based on an existing FPGA development board. It needs two types of camera boards, i.e. a camera with a rolling shutter and a camera with a global shutter – a global shutter refreshes all the image lines simultaneously (snapshots), while a rolling shutter refreshes the image lines one by one (scanning). There is a parallel interface between the cameras and the development board. A break-out board is needed to connect the camera boards to the development board. The FPGA takes care of the interface with the cameras and the process steps of the stereovision process up to the point that a disparity map has been generated.

The results from each process step are written to RAM memory on the development board. The interface between the development board and the PC is achieved via ethernet and UDP (User Datagram Protocol). The PC provides a user interface, visualisation of data and a way to calibrate the vision system. The user can also use the PC to write settings to the camera.

Point Cloud Library

A point cloud is a collection of n-dimensional points (Figure 2). In the case of 3D vision, this is usually a collection of 3D points. To acquire a point cloud, a 3D camera system is used. This could be a TOF camera, a stereovision system or a structured-light camera. PCL is a cross-platform open source C++ library for processing point clouds. It is also available for ROS.

The NHL Centre of Expertise in Computer Vision is integrating the PCL into an existing 2D vision program. The result will be a test facility that enables experiments with 3D as well as 2D algorithms.

Demonstrators

Jenga Robot

Jenga is a game that consists of a number of wooden blocks that are used to build a tower. Players take turns to remove a block from the tower. The removed block must be placed at the top of the tower. When the tower collapses, the game is over. The tower then has to be rebuilt. This game is being used as a demonstrator to highlight the possibilities of 3D vision.

The system uses an ABB robot and a TOF camera (MESA SR4000). The players order the robot to remove a block from the tower. The robot places this block on top of the tower in a position given by the players. Once the tower collapses, the robot rebuilds it. The main tasks of the vision system concern the recognition of blocks, their position and orientation, deciding which block has to be taken first and telling the robot controller this.

Agile Manufacturing

The HUUniplacer is a delta robot that was developed by the HU. It is being used as a platform for a demonstrator. In the demo, four crates are being used. Two of those crates are empty, while one of the crates is full of blue marbles and the final crate is full of red marbles. In the demo, the delta robot distributes the marbles over the four crates according to several predetermined patterns. The system needs to identify and locate the crates. The system must monitor whether a crate is moved or removed from the field of view. It uses a camera that provides a top view and a camera that provides a bottom view. The vision sensors used are USB cameras. HU has written a Linux driver for the cameras in order to communicate with OpenCV. Each crate has a QR code that is used to identify and locate the crate.

Status

Stereovision

The camera boards and the break-out board have been designed and are being manufactured. The firmware for a system with cameras with a global shutter has been written and is ready to be tested. The test software is not completely functional yet. The system calibration still has to be implemented in the software. After successful tests, the vision system will be used in follow-up projects (i.e. Medical Robotics, Agile Manufacturing, Jenga Robot, Adaptive Robotics) in a production environment. A schematic that combines the camera boards and a development board has been developed.

Jenga Robot

A first version of the Jenga robot has been tested (Figure 3). The vision algorithms work well. The camera had some distortion because of reflections. Therefore, it was decided to average several camera shots, resulting in a lower frame rate. This had no effect on overall system performance. The resolution of the camera in the X-Y-plane is not enough for



the required accuracy of the system. This problem will be solved mechanically. A camera system with higher resolution would be preferable though. In the near future the TOF camera will be replaced by the stereovision system.

3 *The Jenga robot in action.*

Point Cloud Library

A substantial part of the PCL is available in the test facility. Functionality has been checked by experiments in several demonstrators. This functionality will be used extensively in further experiments, including those with stereovision.

Agile Manufacturing

A fiducial and QR recognition module has been developed for OpenCV. The demonstrator works as defined. In the future, the demonstrator may be fitted with the camera system that is being developed. ■

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- www.ncbi.nlm.nih.gov/pmc/articles/PMC3304120 (Kinect depth data)

UPCOMING EVENTS

7 November 2013, Den Bosch (NL)

Bits&Chips 2013 Embedded Systems

For the 12th edition, Bits&Chips publisher Techwatch has joined forces with INCAS³, a research institute developing high-tech sensor systems, to organise the Embedded Systems conference. The topics of this year's conference are big science, co-development, distributed sensing, electric vehicles, healthcare and 'smart cities'.



WWW.EMBEDDED-SYSTEMEN.NL

21 November 2013, Utrecht (NL)

Dutch Industrial Suppliers Awards 2013

Event organised by Link Magazine, with awards for best knowledge supplier, best logistics supplier and best customer.

WWW.LINKMAGAZINE.NL

3-4 December 2013, Veldhoven (NL)

Precision Fair 2013

Thirteenth edition of the Benelux premier trade fair and conference on precision engineering. Some 260 specialised companies and knowledge institutions will be exhibiting in a wide array of fields, including optics, photonics, calibration, linear technology, materials, measuring equipment, micro-assembly, micro-connection, motion control, surface treatment, packaging, piezo technology,



Precision Fair 2013

precision tools, precision processing, sensor technology, software and vision systems. The conference features over 50 lectures on measurement, micro-processing, motion control and engineering. The Precision Fair is organised by Mikrocentrum.

WWW.PRECISIEBEURS.NL

6 December 2013, Eindhoven (NL)

Innovation & Technology Conference

The impact and results of the work of the Centres of Excellence of the 3TU Federation (the three Dutch universities of technology) will be presented to partners in industry, government and academia. Central themes are High Tech & Health and Energy & Mobility.



WWW.3TU.NL

11-12 December 2013, Ede (NL)

Netherlands MicroNanoConference '13

Conference on academic and industrial collaboration in research and application of microsystems and nanotechnology. The ninth edition of this conference is organised by NanoNext.NL and MinacNed.

WWW.MICRONANOCONFERENCE.NL

26-27 February 2014, Veldhoven (NL)

RapidPro 2014

The annual event for the total additive manufacturing, rapid prototyping and rapid tooling chain.



WWW.RAPIDPRO.NL

11-14 March 2014, Utrecht (NL)

ESEF 2014

The largest and most important exhibition in the Benelux area in the field of supply, subcontracting and engineering.

WWW.ESEF.NL

7-8 May 2014, Den Bosch (NL)

High-Tech Systems 2014

The second edition of this event focuses on the high-tech systems industry in all European areas with significant high-tech roadmaps. It entails sectors and topics like advanced system engineering and architecture, precision engineering, mechatronics, high-tech components system design as well as advanced original equipment manufacturing (OEM).



WWW.HIGHTECHSYSTEMS.EU

22-23 May 2014, Aachen (DE)

28th Aachen Machine Tool Colloquium

The Aachen Machine Tool Colloquium (Aachener Werkzeugmaschinen-Kolloquium, AWK) has established itself as an important platform for exchanging future perspectives for production technology. The general topic of AWK 2013 is 'Industry 4.0 – The Aachen Approach', focusing on the potential as well as risks of implementing a cross-linked, intelligent production and demonstrating the technical realisation by means of case studies.

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OPERATOR-ROBOT COLLABORATION FOR FLEXIBILITY, ACCURACY AND SPEED

In the micro-technology industry, most assembly tasks to build miniaturised products are performed by hand by highly qualified operators. Using standard machines to handle and accurately assemble micro-components is difficult, and human expertise and flexibility are still required. However, miniaturisation and production growth require more and more accuracy and productivity, and operators need help. A new robotic system, based on the concept of cobotics, combines the accuracy and productivity of the robot with the flexibility and smartness of the person operating the robot.

DAVID HÉRIBAN

In real micro-assembly tasks, two major issues need to be resolved to increase industrial interest in robotic systems. The first one is the lack of accuracy of common industrial robots and grippers: handling 100µm parts with a robot is still a difficult task. Robots, grippers and sensors have to be improved or adapted to be able to reach the high level of performance required. The second issue is the difference in flexibility between human and robot operation. Thanks to our brain, the human hand is the most flexible tool we know. For a robot's control system to be used more easily, it has to be improved.

Without decent artificial intelligence, one of the best ways to improve flexibility is to combine human operators and robots to perform micro-assembly tasks.

Micro-manipulation issues

Assembly processes require handling capabilities of components, and the miniaturisation of components changes the way of assembling and handling them. Micro-manipulation is a major issue in the high-accuracy assembly of miniaturised products. First, classical handling systems (e.g. tweezers for manual handling, vacuum grippers on robots for automated handling) are usually not accurate enough in terms of the size of the object. Industrial robots are designed to copy human gestures, and their accuracy is no better than several tens of micrometers. For a 200µm object, the size of a mechanical fixture is close to 10-20 µm, in which case the accuracy needed to perform the assembly is below 1 µm.

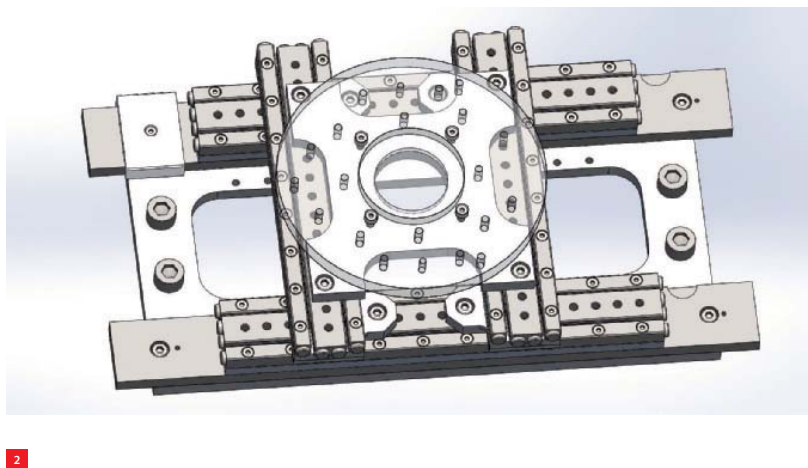
Besides accuracy, size itself is responsible for numerous disturbing effects. Capillarity (Figure 1), electrostatic and Van der Waals forces are much more important than weight: objects stay in contact with grippers, even if they are released. And last but not least, there are drawbacks with the vision of microscopic objects. With photonic microscopes, the highest magnification is limited by their

AUTHOR'S NOTE

David Hériban is the founder of Percipio Robotics, based in Besançon (France). He previously worked on micro-assembly robots as a research engineer at the FEMTO-ST Institute (France), but once he built a fully functional robot there, he decided to leave and set up his own company to build industrial robots based on this technology. Now, five engineers use their know-how in robotic micro-assembly to create robotic systems that are able to grasp micro-components (5 µm to 2 mm) and assemble them in micro-products.

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- 1 *50µm glass microsphere glued by capillarity to the gripper's right finger.*
- 2 *A robot 3-axis modular table.*
- 3 *Piezoelectric tweezers.*

different manufacturers. It is then possible to build a flexible and modular robotic structure with an accuracy of below 2 µm for a defined specification of the number of DoFs, stroke, speed, acceleration, repeatability, straightness, etc.

Micro-grippers

The second way to increase accuracy during a micro-assembly task is to improve the behaviour of object handling and release. Two kinds of grippers are used for micro-assembly: manual tweezers for small or medium series of products for complex objects (e.g. the watch industry) and vacuum grippers for simple shapes (e.g. planar surfaces, spheres) mostly for large series (e.g. microelectronics). Even if the vacuum gripper is carried by an accurate robot, the accurate assembly of sub-millimeter parts is difficult. This tool is disturbed by the object's behaviour at the micro-scale, especially by capillarity and low mass. In the air at normal conditions, objects stick to the vacuum gripper's needle, which means they then need to be blown off to be released. But low mass means low inertia and being blown off could displace the micro-object far from its target. In that case, using tweezers is an interesting way to grasp objects; here, a very small contact surface is used to avoid surface force disturbance. To place tweezers on accurate robots, the French research institute FEMTO-ST has developed a specific technology based on piezoelectric actuation (Figure 3).

In the PiezoGripper, two piezoelectric beams are used as the fingers of a pair of tweezers and a specific voltage over the electrodes of the beams causes them to bend with high resolution (about 0.1 µm) and large stroke (more than 200 µm opening). FEMTO-ST has also designed fingertips (in nickel, silicon or polymer) to grasp microscopic objects,

resolution (0.2 µm minimum). Micrometer accuracy requires a microscope instead of classical camera macro objectives, with high illumination, short work distance, and a small depth of field (sometimes objects are seen in focus only within a 2µm depth range).

Flexible high-accuracy robotic platform

The first way to increase accuracy is to move away from industrial robotics and build a robot with much more accurate components. Already being used in research laboratories in the micro-technology sector, compact robotic systems are used for accurate positioning (e.g. optical science, MEMS, microelectronics, etc.). They comprise a single compact and accurate linear and rotation positioner (Figure 2), assembled together in multi-DoF (degree of freedom) robotic systems.

Percipio Robotics has built up extensive expertise on high-accuracy robotic component integration. Aided by specifically developed software, it is possible to assemble and drive any kind of robotics components even from

and compact sensors to provide real-time measurements of the position of each finger. Percipio Robotics got this technology from the institute and improved it to use robotic micro-tweezers in industrial assemblies (see the box for the PiezoGripper's motion principle and specifications).

High-resolution visual system

To be efficient, flexible robots for high-accuracy assembly need computer vision with high-resolution optics. But microscope optics are often difficult to integrate into machines, even more so for compact ones. Plus, the high magnification required by assembly implies a small field of vision, a few hundreds of micrometers wide. To open up the field and make integration easy, Percipio Robotics built a new kind of vision system with high-resolution compact

optics, high-resolution cameras (> 10 megapixels) and specific software.

With this system, cameras observe a 'large' field of view (6 mm wide) while optical resolution on the full image is about 1.5 $\mu\text{m}/\text{pixel}$. To avoid low image refresh on full-scale images, the software downgrades the resolution to the screen resolution. When the assembly task needs to observe a small area, only the field of interest is captured by the camera, in high resolution, at the speed of 25 frames per second. It is then possible to zoom in up to six times on the screen, without touching the camera's objectives, and even move the field of interest at full resolution anywhere in the field (see Figure 5).

PiezoGripper motion

The PiezoGripper used by Percipio Robotics is different from others tweezers for one reason: obviously, fingertips can move horizontally to grasp objects, but they can also move vertically; see Figure 4. This original motion is used to guarantee alignment of the fingertips. It is then possible to replace common monolithic grippers (i.e. actuator and fingertips on the same device) with assembled grippers, where fingertips are glued to the actuators. Misalignment in the gluing process is corrected by the gripper's specific vertical motion.

Finally, a large set of fingertips can be used on this piezogripper for a wide range of applications. The material, thickness and size of the fingers can be easily changed, as can the initial gap between the fingers (from 0 μm to 4 mm); see Table 1 for specifications. Finger tips are delivered according to application requirements as consumable products. Damaging fingertips is no longer an issue.

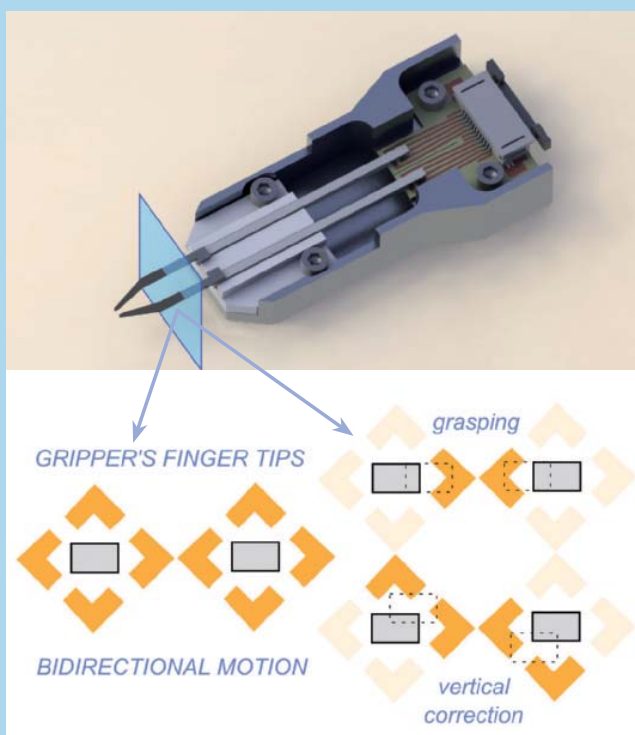
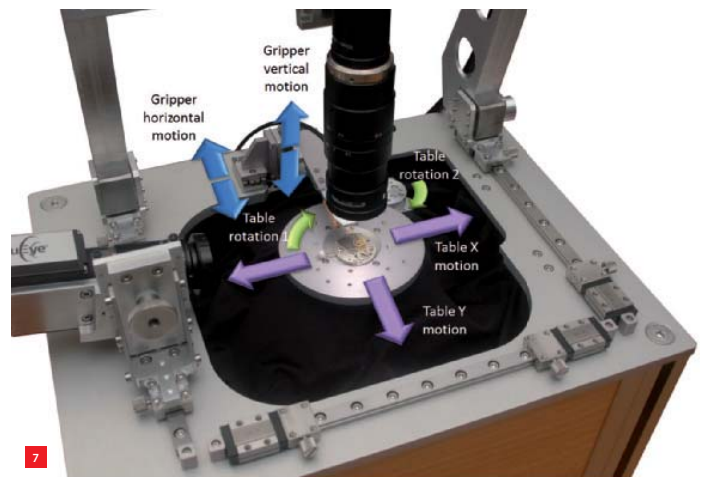
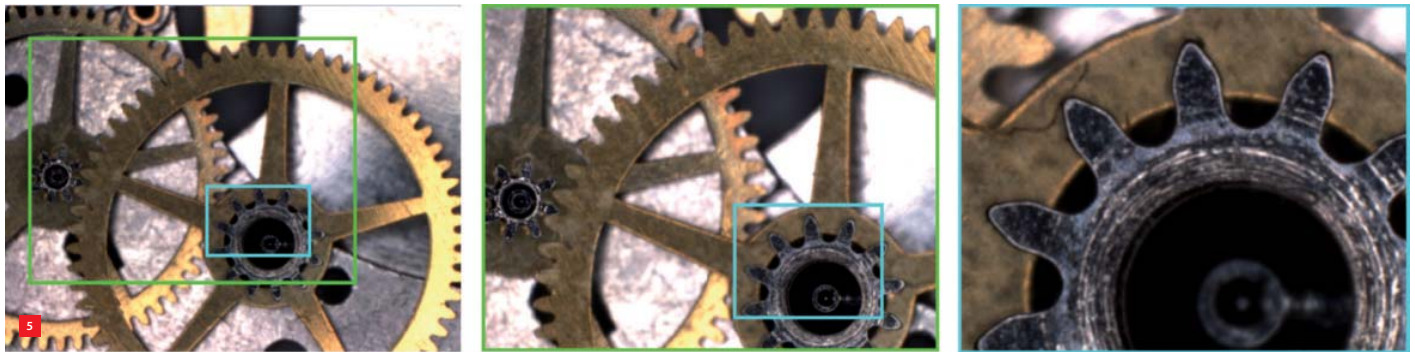


Table 1 PiezoGripper specifications.

Stroke	200 μm to 1 mm
Blocking force	up to 80 mN
Resolution	50 nm
Repeatability (closed loop)	$\pm 1 \mu\text{m}$ (3 σ)
Initial gap	0 μm to 4 mm
Close time (full stroke with closed loop)	35 ms

4 Horizontal as well as vertical motion.



- 5 Zoom on a full-scale image.
- 6 Overview of the platform.
- 7 CHRONOGRIP robotic motion.

Integrated assembly platform

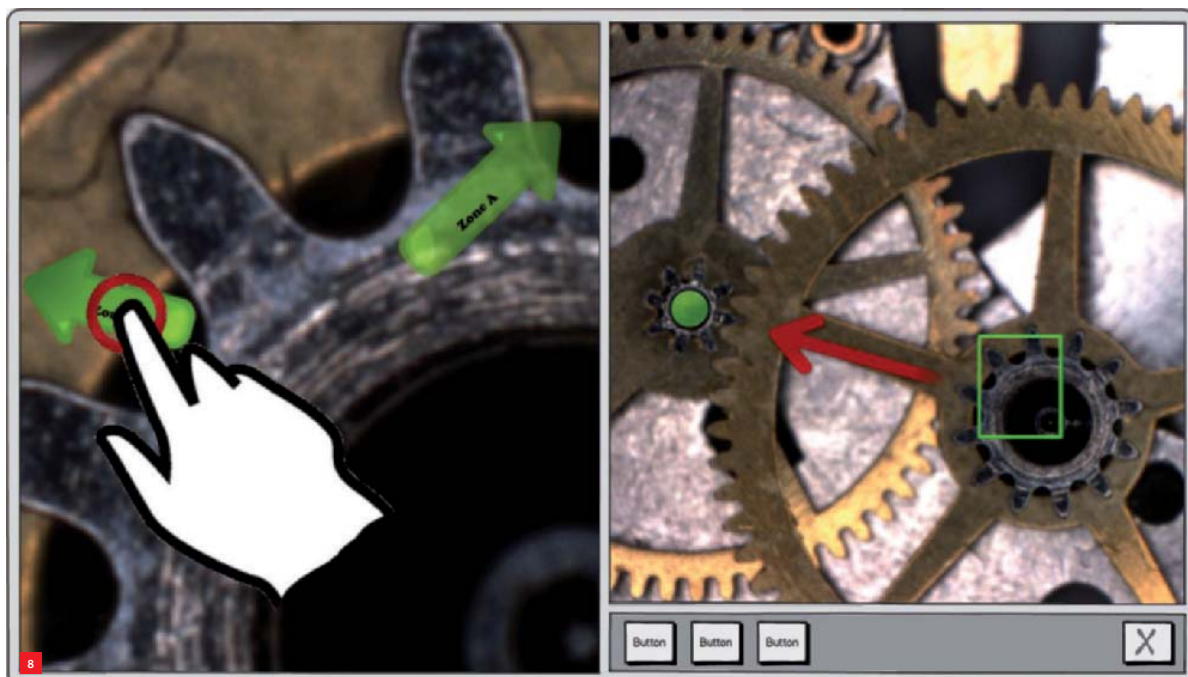
Once all these pieces of technology are available, the final path to micro-assembly is to build a compact, accurate and flexible robotic system to perform micro-assembly tasks. Percipio Robotics has already completed this step with the CHRONOGRIP, a fully integrated robotic platform with modular robotics, piezogrippers and a high-resolution visual system (see Figure 6). This device is compact (it can be placed on a table), can be easily transported in a protective case, is easy to mount and start (less than five minutes) and is available in different configurations depending on the application.

In the standard version, the table moves and rotates in the horizontal plane relative to the gripper and the cameras (see Figure 7). The gripper is positioned by two linear axes. The robot has a motion resolution of $0.1 \mu\text{m}$ and an accuracy of $\pm 2 \mu\text{m}$ with closed loop (visual servoing). Axis speed can be set from $1 \mu\text{m/s}$ (precise task) to 10 mm/s .

The power of cobotics

The CHRONOGRIP robotic platform is now being used for micro-assembly tasks. Even if technological improvements were made to allow flexible and accurate operation, operating the robot is still a complex task. In industrial robotics, numerous robots are programmed offline and execute the same task again and again in open-loop processes. Task analysis is increasingly needed during the operation to close the loop, with computer vision used to operate the robot (e.g. pick & place). At a micro-scale, computer vision is very difficult to use (small depth of field, heterogeneous light, diffraction), and achieving a fully automated micro-assembly task can be too time-consuming.

Percipio Robotics took a step forward by using the principle of cobotics ("collaborative robotics") on micro-assembly tasks. Cobotics is the collaboration of a human being and a robot to perform a task. The robot is operated by the



8 Touchscreen interaction.

operator, but not in a master/slave mode. The robot uses its sensors to send a full set of information to the operator (e.g. vision, haptics, and augmented reality) and can correct operator's commands to improve motion behaviour (e.g. compensating for a shaky hand). This interaction between robot and operator is the most flexible way of creating accurate and fast micro-assembly tasks. The robot needs the smartness and flexibility of the operator to achieve its task, while the operator needs the accuracy and stability of the robot to move the micro-gripper

The CHRONOGRIP is in fact operated by an operator who is using a joystick and a tablet PC with touchscreen (see Figure 8). The joystick is used to move the robot, and the tablet PC is used to view the video stream from the camera, and operate the zoom and image position.

Further developments

Percipio Robotics is working on a new haptic device for tweezer tele-operation to give operators a better experience than the one they have with the joystick. The French research laboratory ISIR is involved in this work and the first results are expected in 2014. Other R&D work on augmented reality that has already begun will help the operator to be aware of the robot's position instead of reading position sensors.

Nowadays, most experts in the field agree that the future of industrial micro-assembly operations is strongly linked to robotics. To fulfil the requirements on flexibility and fast reconfiguration, robotics need something more, and cobotics can provide an exciting technological and social solution. ■

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VALUABLE MANUFACTURABILITY COURSE FOR ENGINEERS

Sharing knowledge regarding manufacturability – how precision components are made – is highly relevant to designers and engineers developing precision systems. Dutch high-tech firms therefore greatly appreciated the recent 5-day LiS Academy Summer School on Manufacturability, a joint initiative of DSPE and LiS Academy.



ERIK KNOL

Appreciation from industry

The high-tech industry in the Netherlands is ambitious. One important aspect in fulfilling the Dutch high-tech industry's export targets is sharing knowledge to facilitate the development, construction and marketing of high-tech systems. Sharing knowledge regarding manufacturability – how precision components are made – is highly relevant to designers and engineers developing precision systems that are “designed for manufacturability”. This is the main reason why the recent 5-day course “LiS Academy Summer School on Manufacturability – edition 2013” was greatly appreciated by Dutch high-tech firms. The Summer School is an initiative of DSPE and LiS Academy (part of the Leiden Instrument Makers School, providing professional

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- 1 Technology for micro-milling using mills with diameters of tenths or even hundredths of millimeters is available now. Reliably deploying this technology requires correctly matching people, machines, measurement tools and software. (Source: TNO)

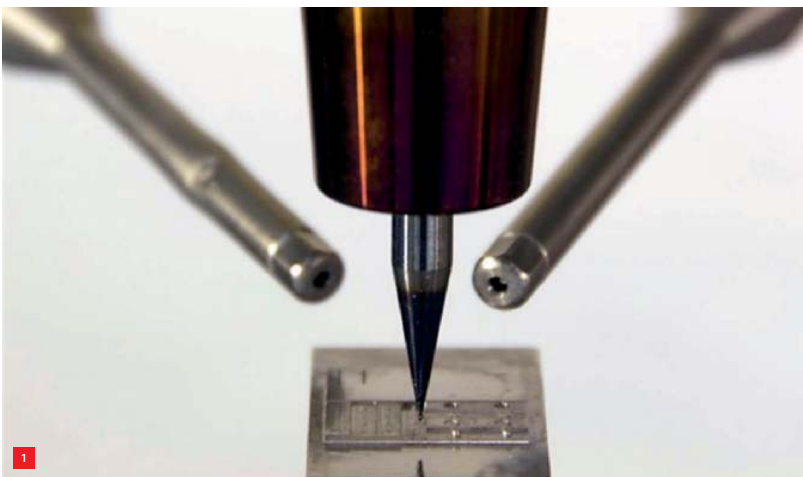
training). The attendees, mainly from high-tech industry, gave the course an average score of 8 out of 10.

Focus

The 5-day Summer School targeted young professional engineers working in high-tech companies. The main goal of the course was to give in-depth insights about basic manufacturing techniques like milling, turning, grinding, EDM (electro-discharge machining / spark erosion), metal casting and sheet metal working – not only by sharing theories with the support of guest speakers from the industry, but also by visiting companies, having a group-based discussion session with senior engineers / technicians, and getting practical training, provided by LiS instructors active in the field of CAM software, conventional turning, CNC milling, and CNC measuring. The attendees greatly appreciated the visits to Dutch companies Hittech Gieterij Nunspeet (aluminium casting company in Nunspeet) and Suplacon (sheet metal working company in Emmeloord). In addition, guest speakers, including from Hittech MPP, Ter Hoek Vonkerosie, Hembrug, ECN and TNO, gave state-of-the-art information about CNC milling and CNC EDM, hard turning, grinding, and beyond-state-of-the-art (experimental) developments like micro-milling (see Figure 1).

Attendees

The aim of the Summer School was to have a small group of young professional engineers learn more about manufacturing techniques and support each other in the learning process. Therefore, the course was limited to





2 Attendees of the Summer School.
3 Many kinds of aluminium alloys are available for manufacturing the required products, for example alloys suitable for thin-walled constructions or for high surface quality. (Photo courtesy of Hittech Gieterij Nunspeet)

twenty attendees. The course was fully booked and unfortunately there was a reserve list of engineers who were unable to join the course. Most of the attendees were engineers. Over 50% had an academic background in engineering /science, one-third a professional bachelor's degree in engineering, and roughly 10% a vocational-level educational background. The following companies / institutes gave one or more of their engineers the opportunity to attend the Summer School (in alphabetical order): ASML, Bronkhorst High-Tech, Frencken Engineering, Hittech Multin, IBS Precision Engineering, Mapper Lithography, Maris College, NTS Mechatronics, TMC Manufacturing Support, TT Engineering and VDL ETG; see Figure 2. The attendees were positive about the Summer School course.

Highlights

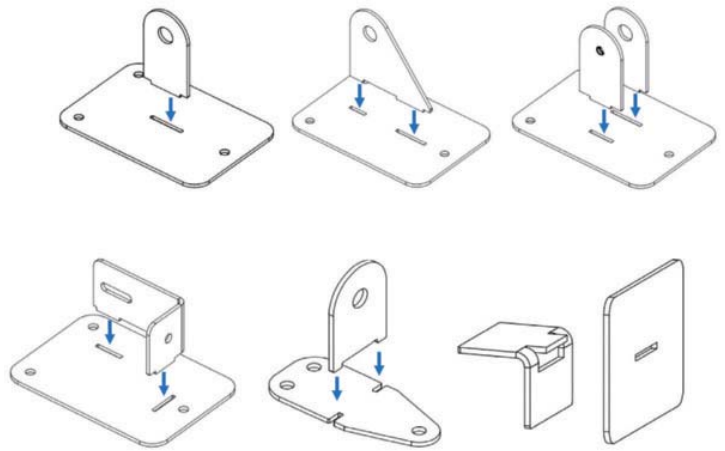
The visit to the aluminium casting company made a great impression on the attendees (see Figure 3), although beforehand various attendees had viewed casting as a less relevant technology for the high-tech precision industry. Hittech Gieterij Nunspeet showed cleverly designed and casted frames for use in high-tech optical instruments. In addition, the company gave a good explanation of the do's and don'ts regarding the design of products to be casted.

In preparation of their visit to the sheet metal company Suplacon, the attendees were invited to design a sheet metal tablet holder. Several of these designs were then actually manufactured at Suplacon. It was interesting to have an open-floor discussion on the designs created by the attendees. In addition, Frank ten Napel (Suplacon) and Piet van Rens (Settels Savenije van Amelsvoort) shared valuable

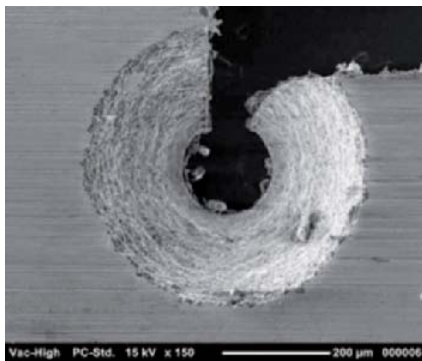




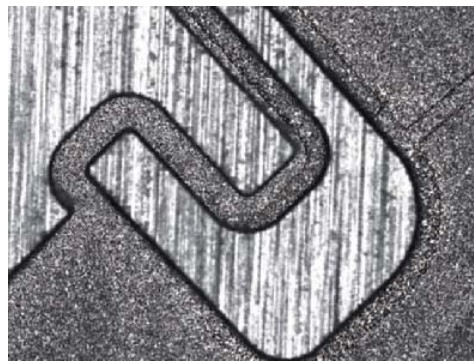
4a



4b



5a



5b

4 Examples of smart sheet-metal design. (Illustrations courtesy of Suplacon)

(a) Stainless-steel frame construction for the medical industry. Built out of sheet metal, laser cut, bent and welded, and with threaded inserts. Developing frames in sheet metal gives the engineer great dimensioning and design freedom.

(b) Mortise and tenon joints in sheet metal reduce assembly times and error probability, while facilitating dimensional accuracy.

5 Examples of micro-EDM. (Courtesy of Ter Hoek Vonkerosie)

(a) Conical contour made to 1 micron accuracy. The narrow entrance to the hole, 0.08 mm wide, has been achieved with wire-EDM using 0.05 wire.

(b) Very small details, such as a groove width of 0.05 mm and surface roughness (R_a) of 0.20 micron, can be achieved.

insights about basic design and engineering rules regarding sheet metal (see Figure 4), with suggestions regarding mortise and tenon joints and (theories regarding) sheet-metal construction principles.

EDM was very well highlighted by Gerrit ter Hoek (Ter Hoek Vonkerosie). The topics he addressed included the various EDM techniques available, the high accuracies possible with EDM and cost aspects related to the manufacturing of high-tech precision parts with EDM (see Figure 5). During the short visits to the company Taxx and the fine-mechanical engineering department at Leiden University, the attendees saw EDM in practice.

Positive experience

Judging by their reactions and feedback, the LiS Academy Summer School on Manufacturability was a positive experience for the attendees. Strong aspects of the course

were the balance between theory and practice, the strong line-up of course partners from industry and academia (including Hittech Group, Suplacon, Hembrug, TNO, ECN, Settels Savenije van Amelsvoort, Leiden University, and Ter Hoek Vonkerosie), and the support of DSPE (co-initiator of the course), Brainport Industries and sector organisations FME and Dutch Precision Technology (DPT). In the coming months, LiS Academy will elaborate its courses for 2014. We will keep you posted on the progress in preparation of the 2014 edition of the LiS Academy Summer School. ■

LOW COST, SMART TECH

The continuing aging of the population keeps putting pressure on the healthcare system, making it more difficult to provide acceptable standards of care. Robotics can be used to perform simple tasks such as opening a door or a drawer without consuming the time of staff, for example in a nursing home. A multi-purpose robotic arm has been developed to explore its potential for low-cost production.

RAMON AMMERLAAN

The design of the robotic arm (Figure 1), a simplified version of a more advanced design, was based on standard servo units in order to make it as low-cost as possible. It features seven degrees of freedom (DoFs) and the overall length of the arm is equal to that of a human arm. It can lift a payload of 0.5 kg (excluding the end-effector), is lightweight and, more importantly, safe when used by qualified personnel.

Servo unit

The servo units selected for arm control are Dynamixels, a popular type in robotics. Despite its small size, this servo unit is able to generate a relatively high torque thanks to the internal gearbox. Other strong points of the Dynamixel are its position and speed control and feedback, easy and fast communication due to the so-called Daisy Chain Link and the ability to link units to each other, giving them specific orders without the use of extra controllers. This prevents a lot of wiring, which reduces weight (and assembly complexity) as well.

1 The low-cost robotic arm.



Design of the joints

Most of the weight is concentrated in the base (shoulder); this gives the arm maximum stability, while it does not influence the servo units. Most of the parts have been created out of milled aluminium or sheet metal to keep the weight to a minimum; at the same time, the construction of the robotic arm provides sufficient stiffness and stability.

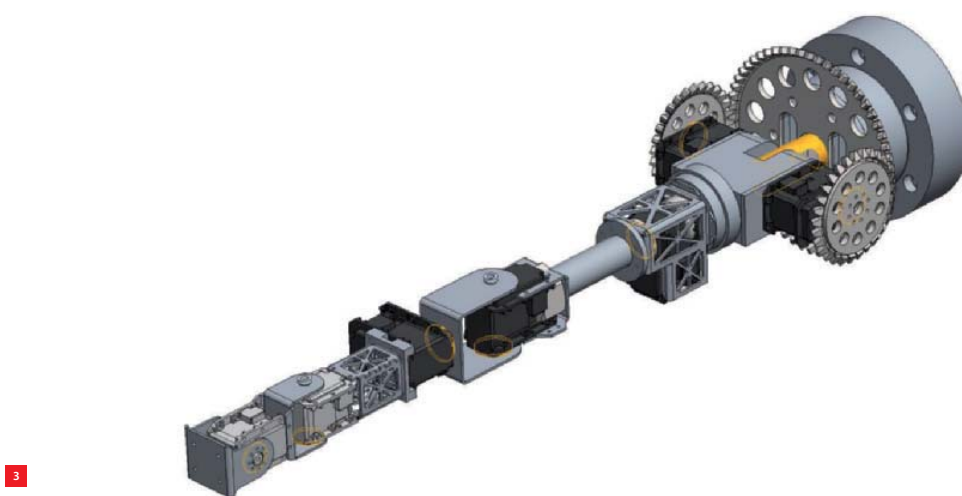
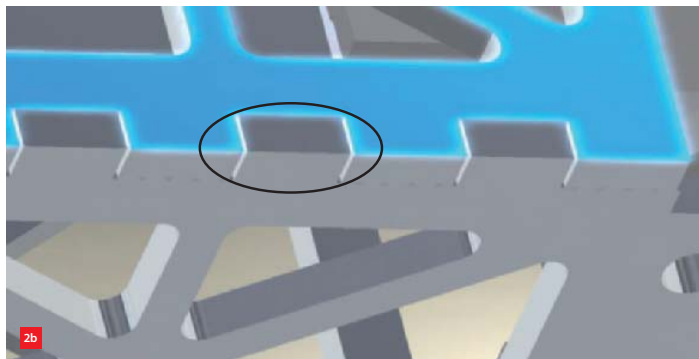
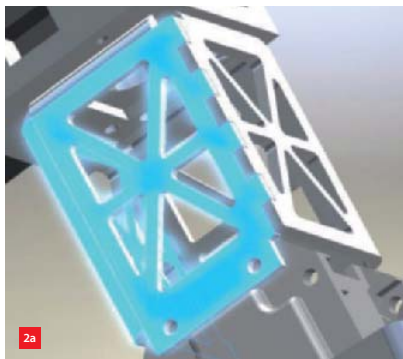
The lower arm consists of symmetric sheet metal (Figure 2). The symmetry facilitates the production and construction. A gap of ± 0.2 mm has been allowed for in the design for welding the parts together in order to improve resistance to torsion. For easy welding, the sheet metal plates are positioned with respect to each other by battlements.

AUTHOR'S NOTE

Ramon Ammerlaan works as a mechanical engineer at Hittech Multin in Delft, the Netherlands. He is enrolled in a dual pathway at the Hague University of Applied Sciences, combining his work with the pursuit of a Bachelor's degree in Mechanical Engineering. The work described in this article was done at Demcon advanced mechatronics in Oldenzaal (now established in Enschede, the

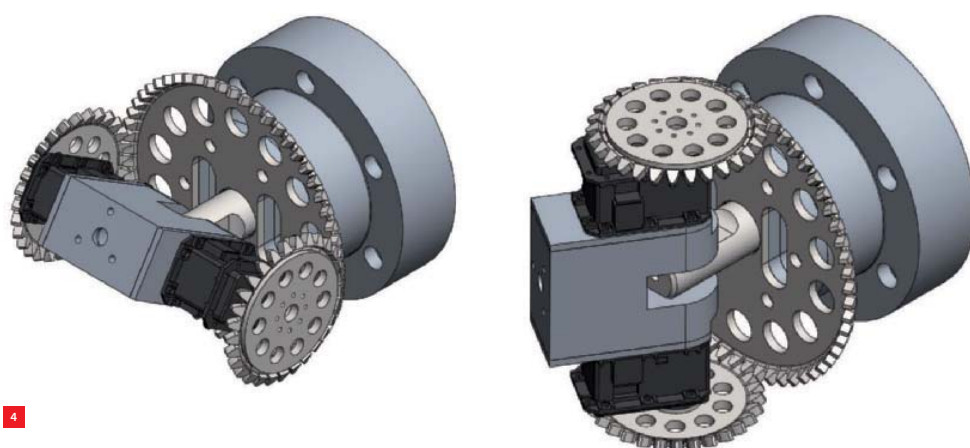
Netherlands). It was part of Ramon Ammerlaan's graduation project during his Mechatronics course at the Leidse instrumentmakers School (LiS, Leiden Instrument Makers School). He expresses his gratitude to Hermes Jacobs, mechatronic systems engineer at Demcon, for his support.

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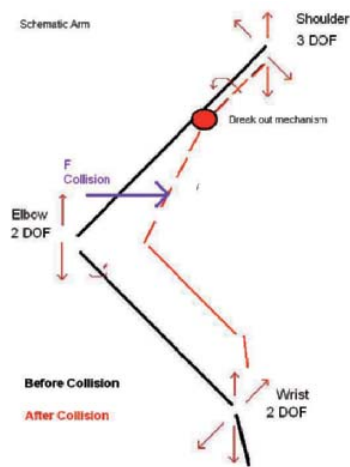
- 2** Sheet metal construction of the lower part of the robot arm.
(a) Stiff sheet metal frame.
(b) Close-up showing fixation of the plates before welding.
- 3** Rotational DoFs of the robot arm.
- 4** The differential of the shoulder joint in two views.

The joint configuration of the robotic arm differs from that of the human arm. In particular, gimbal joints like a human shoulder and wrist are complex for actuation in a robotic arm. For this reason the robotic shoulder has two DoFs, which are actuated by the two Dynamixel with the tooth gears. The rotation of the elbow is realised in the upper arm of the robot arm. Also, at the robot wrist the positions of the rotations differ from those in humans. Figure 3 shows the rotational DoFs of the robot arm.



The shoulder joint is differential driven (Figure 4). The differential can control DoFs by using two servo units. The big gear (active gear) remains in one position; it is fixed and cannot be moved. The small gears (pinion gears) are assembled onto the servo units. Once the servos start rotating in the same direction, the shoulder makes a rotation around one axis. If the servos are rotating in opposite directions,

the shoulder joint makes a rotation around another axis. This results in the arm going either up/down or left/right. Due to the differential, the movements of the shoulder joint will look more natural. In order to limit the number of parts and weight, no differential is used for the wrist. The parts have been



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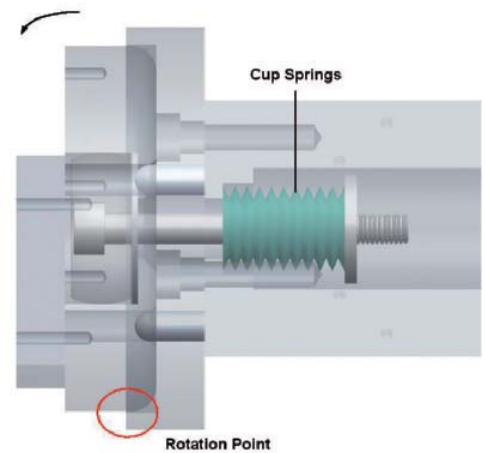
designed for fast and easy production to reduce cost. The robot arm is relatively easy to fabricate and assemble, due to the simple design. Plain bearings have been chosen for their low cost and weight.

Breakout mechanism

In order to make the arm safer to use, a breakout mechanism was developed (Figure 5). There is always the possibility of a collision with the robot arm. The best option would then be for the robot arm to stop moving entirely, but this is impossible due to the chosen servo and movement units, and using additional sensors to prevent collision would make the arm more expensive. The breakout mechanism was designed to decrease the amount of collision force if the arm were to collide with a person or object, by breaking most of the arm mass away.

The breakout mechanism has an effect comparable to that of breaking a bone in the upper arm. But after a collision, this robot arm heals itself instantly by 'clicking back in' its mechanism. The upper arm is held in place by cup springs in the breakout mechanism (Figure 6). If the collision force exceeds the force provided by the cup springs, the mechanism will break out. The reason for adopting cup springs is that they are compact and stackable. This is convenient for tweaking the mechanism; if it is still too stiff, more cup springs can be added, making the mechanism less stiff.

In other words, the stiffness and the breakout angle of this mechanism can be easily adjusted by changing the number of cup springs. Moreover, cup springs have a relatively high ratio of force to size/mass compared to wire springs.



6

5 The breakout mechanism.

6 Design of the breakout mechanism with the cup springs.

If a collision occurs and the impact force is high enough, the mechanism 'rotates' with the radius of the part around the fixed part, causing it to break out, reducing the collision force exerted on the person or object in question.

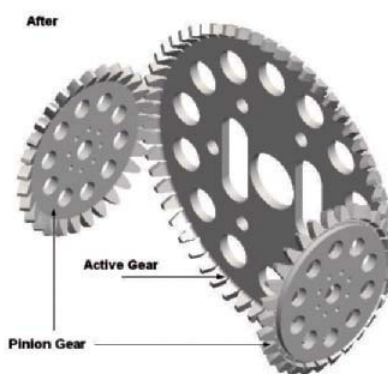
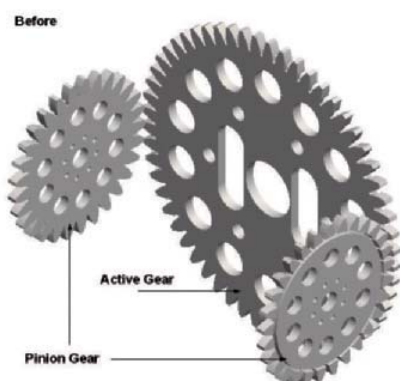
Gears

Initially, the plan was to use real bevel gears for the robotic arm. Their design was optimised for low weight, but the overall cost would be high, the lead time would be long and the design did not meet the concept of a low-cost robot arm. An alternative was designed and realised for only a fraction of the cost (approximately ten per cent, for single-piece orders) of real bevel gears. The new gear design was based on the bevel gears originally chosen. The ratio and amount of teeth are the same, and so is the module (pitch diameter divided by the number of teeth). The design of the involute is based on the centre of the original gears. This was done so the gears would run smoothly without having too much backlash.

The idea was to take a stainless steel plate, cut out the teeth with a laser and bend the teeth; see Figure 7. Since the plate is still flat, a way had to be found to only bend the teeth of the gear – quite a challenge for a 5mm thick plate. As it is convenient if the diameter for bending 'finds itself', a groove was cut out on a lathe (Figure 8).

There are several reasons for this groove:

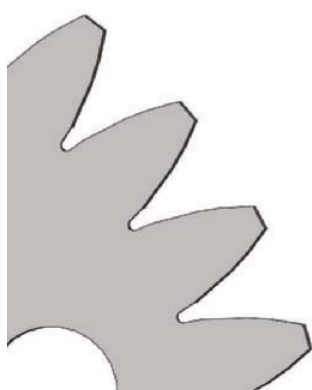
- The change in thickness, from 5 to 2.5 mm, offers the weakest spot as the natural position for bending, so bending becomes predictable.
- The amount of pressure needed to bend the gear decreases because of the reduced thickness.
- Since the gears have to be bent on a diameter, the groove facilitates creating short bending lines, as shown in Figure 9.



- 7 Gear configuration for the robotic arm.
(a) Before bending.
(b) After bending.
- 8 Facilitating 'natural' bending of the gears.
(a) Tooth profile.
(b) Groove for bending (blue highlight).
- 9 Bending line in the groove.
(a) Theoretical.
(b) Actual.

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7b



8a

8b

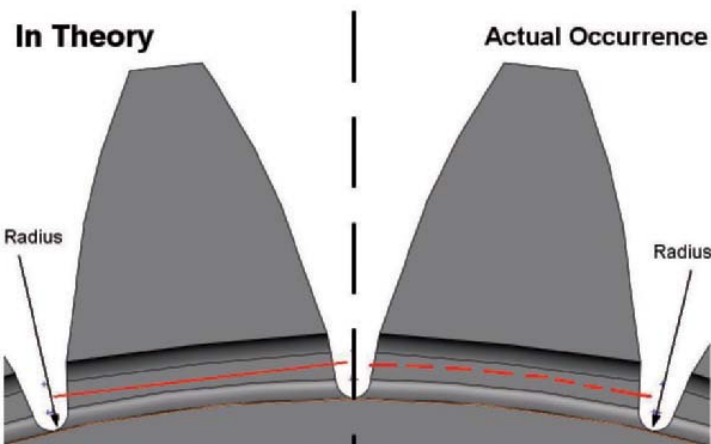
Gear bending tool

In order to bend the teeth, an adjustable tool has been designed and produced (Figure 10). Although the tool is relatively simple, it works perfectly to bend the gears. Once pressure has been applied on the compression tool, the alternative gear will bend according to the model underneath. The challenges were how to make this tool and how to maintain the gear aligned in the centre, to ensure that all teeth are equally bent and the gear stays symmetrical.

In order to keep the alternative gear aligned in the centre of both the compression tool and the model, an axis sticks out of the compression tool. The axis is made in one piece with the compression tool to keep the alignment more accurate. The diameter of the axis is a sliding fit with the hole in the alternative gear; the hole in the model is made to be exactly the same diameter as the gear.

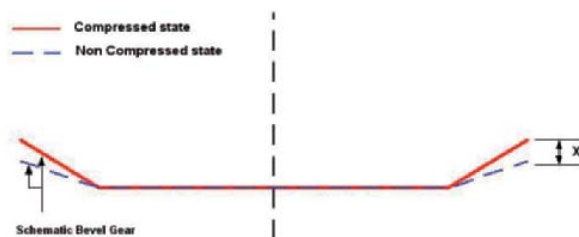
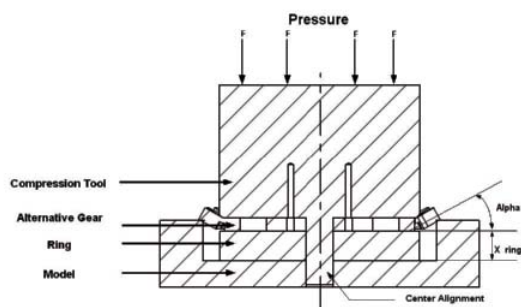
The remaining challenge was to make this tool adjustable to the required angle. For this option a ring was made. The compression tool is pressing the gear on the ring, lying on top of the model. By changing the thickness of the ring (X ring), the angle (alpha) of the gear changes. For example, if the ring is in one line with the top line of the model, no angle can be bent. If the ring is lower than the top line of the model, the gear's angle will increase.

There is another reason for this adjustable tool. Any material that is bent will never remain in this position. There will always be a certain amount of springback. The red line in Figure 11 indicates the gear when it is still being compressed. Once the pressure is removed from the gear, it will go to the non-compressed state, indicated by the dotted blue line. There is a difference x in height and hence the angle changes as well. As this is inconvenient, the ring has been made adjustable too.



9a

9b



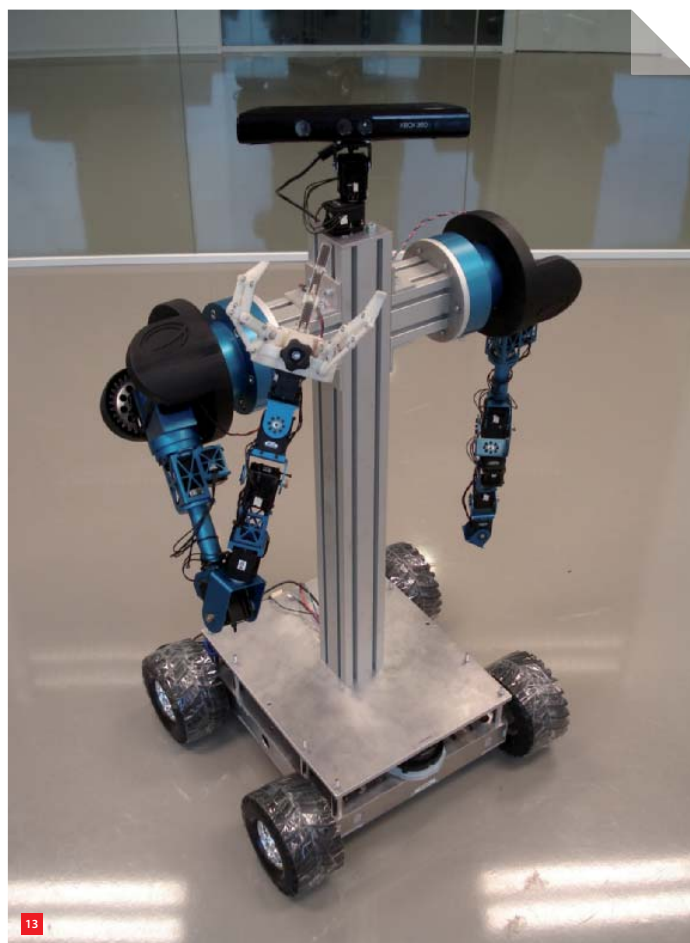
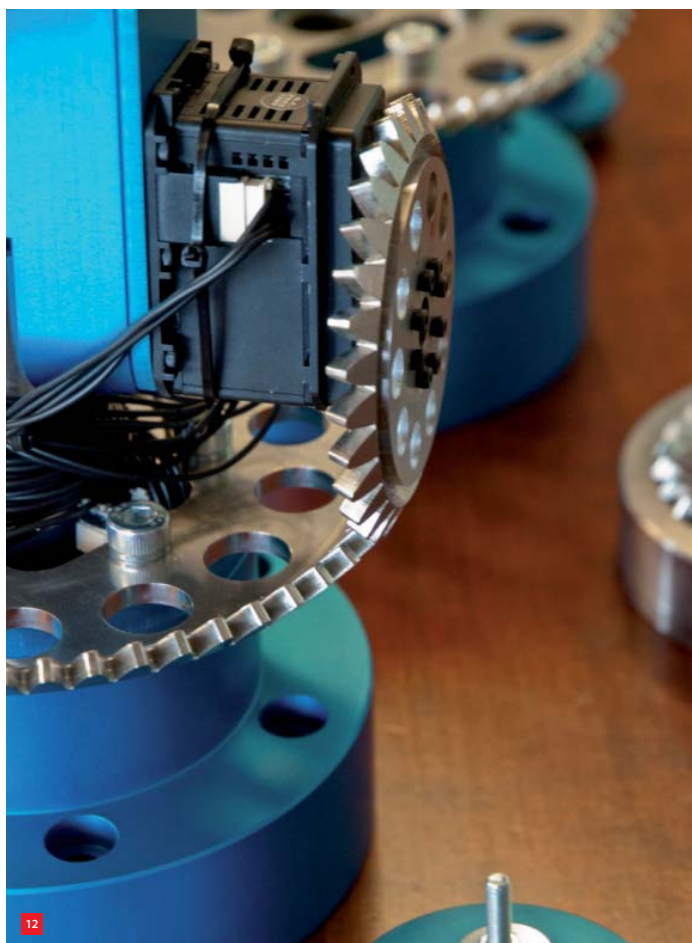
Bending was performed using a practical approach, instead of doing calculations on the amount of springback. Figure 12 shows the realisation of the final gear configuration.

Current status

With support of Demcon, students have designed and built a prototype of an end-effector gripper. The fingers have the

freedom to adjust around the grasped object to ensure a firm grip. The system is placed on an autonomous 4-wheel-driven platform (Figure 13). An Xbox Kinect is used as a sensor. The platform can move autonomously within a defined environment and can recognise QR codes. ■

- 10 Gear bending tool.
- 11 Spring back (to the non-compressed state) after bending.
- 12 Close-up of the configuration with bent gears.
- 13 The robot arm provided with an end-effector gripper and mounted on an autonomous 4-wheel-driven platform.



CPE COURSE CALENDAR

COURSE	CPE points	Provider	Starting date (location, if not Eindhoven)
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BASIC

Mechatronic System Design (parts 1 + 2)	10	HTI	9 December 2013 (part 1) 7 April 2014 (part 2)
Construction Principles	3	MC	29 October 2013 (Utrecht) 19 November 2013
System Architecting	5	HTI	17 March 2014
Design Principles Basic	5	HTI	to be planned
Motion Control Tuning	6	HTI	20 November 2013

DEEPENING

Metrology and Calibration of Mechatronic Systems	2	HTI	18 November 2013
Actuation and Power Electronics	3	HTI	to be planned
Thermal Effects in Mechatronic Systems	2	HTI	10 March 2014
Summer school Opto-Mechatronics	5	DSPE + HTI	16 June 2014
Dynamics and Modelling	3	HTI	25 November 2013

Specific

Applied Optics	6.5	MC	6 March 2014
	6.5	HTI	to be planned
Machine Vision for Mechatronic Systems	2	HTI	20 March 2014
Electronics for Non-Electronic Engineers	10	HTI	7 January 2014
Modern Optics for Optical Designers	10	HTI	to be planned
Tribology	4	MC	30 October 2013 (Utrecht) 27 November 2013
Introduction in Ultra High and Ultra Clean Vacuum	4	HTI	28 October 2013
Experimental Techniques in Mechatronics	3	HTI	15 April 2014
Design for Ultra High and Ultra Clean Vacuum	4	HTI	25 November 2013
Advanced Motion Control	5	HTI	6 October 2014
Iterative Learning Control	2	HTI	4 November 2013
Advanced Mechatronic System Design	6	HTI	5 February 2014

DSPE Certification Program

Precision engineers with a Bachelor's or Master's degree and with 2-10 years of work experience can earn certification points by following selected courses. Once participants have earned a total of 45 points (one point per course day) within a period of five years, they will be certified. The CPE certificate (Certified Precision Engineer) is an industrial standard for professional recognition and acknowledgement of precision engineering-related knowledge and skills. The certificate holder's details will be entered into the international Register of Certified Precision Engineers.

WWW.DSPEREGISTRATION.NL/LIST-OF-CERTIFIED-COURSES

Course providers

- The High Tech Institute (HTI)
WWW.HIGHTECHINSTITUTE.NL
- Mikrocentrum (MC)
WWW.MIKROCENTRUM.NL
- Dutch Society for Precision Engineering (DSPE)
WWW.DSPE.NL

Milestone: 1,000th CPE certificate awarded

Last month, the 1,000th CPE certificate within the DSPE Certified Precision Engineer training framework has been awarded to Saudith Estela Durango Galvan from ASML, who successfully completed the training "Actuation & Power Electronics". This new three-day training has been set-up by Mechatronics Academy in cooperation with the trainers Rob Munnig Schmidt, Sven Hol and Helm Jansen, and it is offered to the precision engineering community via The High Tech Institute.

One of the objectives of DSPE is to improve the level of knowledge and cooperation in the field of precision engineering in the Netherlands. Therefore, DSPE launched the CPE initiative in 2011. This program aims to promote post-academic technical education. Based on the demands in the market, DSPE has selected and qualified the best post-academic courses for precision engineers. The CPE program reflects the demand for multidisciplinary system thinking, excellent cooperative skills and in-depth knowledge of relevant disciplines. This combined investment in education aims to create a common way of working and to facilitate networking among precision



■ DSPE president Hans Krikhaar (second from the left) congratulates Saudith Estela Durango Galvan in the presence of the trainers Rob Munnig Schmidt (right) and Sven Hol (left). Helm Jansen was not present during the ceremony.

engineers. Many precision engineers have successfully attended certified courses in the program and several participants are already well underway for full CPE certification.

WWW.DSPE.NL/CERTIFICATION

Management acquires majority interest in TEGEMA

With the current management acquiring a majority interest in Tegema, founder Jan van Dijk has transferred control of 'his' engineering firm to managing directors Wim van den Broek and Martin van Acht. "Tegema is now the fully fledged project organisation I envisaged", says Van Dijk (68). As a multidisciplinary engineering firm, Tegema provides its clients with optimum support throughout the whole process, from product idea to market success. Tegema operates in five markets (areas of expertise): high-tech systems, medical technology, factory automation, automotive systems and maritime applications. Tegema works with companies such as ASML, DAF, Fokker, Thales, Mapper Lithography and SeeCubic and also has clients all over Europe.

WWW.TEGEMA.NL

3TU: Innovation & Technology Conference

The impact and results of the work of the Centres of Excellence of the 3TU.Federation (the three Dutch universities of technology) will be presented to partners in industry, government and academia on 6 December 2013 in Eindhoven, the Netherlands. Central themes of the first Innovation & Technology Conference are High Tech & Health and Energy & Mobility.

Presentations include: "Providing care over the internet: Can patients trust it?", "Robotics: The new technology wave to solve real challenges and create new opportunities", and "Cooperative Autonomous Driving: Where are we going?" The programme of the conference also features a technology fair ("Meet entrepreneurs, researchers & innovators showing their products & achievements") and interactive workshops, including one on "The engineer of the future".

WWW.3TU.NL

5-finger hand now also contains electronics

Schunk has optimised its 5-finger hand concept study. The motor controllers have been completely integrated in the wrist of the latest anthropomorphic gripper hand, and therefore very compact solutions are available now. Via defined interfaces, the gripper hand can be connected with the lightweight arm that is already on the market. For mobile applications, the energy supply of the 5-finger hand requires a battery-servable 24 V DC. In the first version the hand is controlled via a serial Bus. Now the gripper hand is available as a left- and a right-hand version.

It is amazing how much it resembles its human model in size, shape, and mobility. By means of nine drives, its five fingers can carry out various gripping operations. Moreover, numerous gestures can be constituted, whereby the visual communication between human and service robot is simplified, which helps to increase the acceptance for applications in the human environment. The use of tactile sensors in the fingers will grant the necessary sensitivity of the gripper hand for mastering gripping and manipulation tasks even in unstructured and unforeseeable environments. Elastic gripping surfaces ensure a reliable hold of the gripped objects.



WWW.SCHUNK.COM

■ An earlier 5-finger hand from Schunk.

Chinese-Dutch Summer School for IC Technology Exchange and High Talent

After last year's summer school on Solid State Lighting technologies in Changzhou, China, this year the International Summer school for IC Technology Exchange and High Talent was successfully held from 19 to 24 August in Xi'an, China. With the support of the Dutch Ministry of Economic Affairs, the Xi'an municipal government, Xi'an Jiaotong University, Northwestern Polytechnic University, Xidian University, and the three Dutch universities of technology, the organisation of this technical exchange programme took place.

Experts and scholars from academia and industry in the Netherlands and Xi'an gave lectures based on the theme of IC key technology, industrial development and personal development in a global world. There was opportunity for discussions on the industrial technology cooperation between China and the Netherlands. The summer school also invited some delegates from universities and corporations from Beijing and Shanghai. With so many experts and talents working together not only the summer school was a

success, but it also promoted the development of the IC industry and it created a network for high-level cooperation in a field that is basic for almost all future innovations.

(Source: Network of Netherlands Officers for Science & Technology (NOST) in China)

NEWS.NOST.ORG.CN

Autonomous robots providing real support to disaster relief workers

When a disaster has occurred, the lack of details on the actual situation and the need to respond quickly make it difficult to use robots. Today's robots still demand too much from the user. Last summer, the partners in the European NIFTi project presented their final interim results on the development of smart robots for relief workers at Amsterdam Airport Schiphol.

software from TNO helps gather and share information about the situation: the right information (requests) to the right person in the right form at the right time. Secondly, TNO supplies the know-how and tools needed to design and test robot functionality effectively together with the end users.

WWW.NIFTI.EU

WWW.TNO.NL

NIFTi is about natural human-robot cooperation in dynamic environments and works on increasing the autonomy of robots, both in navigation and imaging. This should improve the quality of robot operation and place less of a burden on users. Partner TNO supplies the know-how and components for two aspects of the human-robot cooperation. First of all,

■ *Demonstration scenario: a train carrying hazardous chemicals has collided with a bus, while a car is also involved in the accident. First, a mobile robot performs measurements on the hazardous chemicals and looks for survivors in the car.*



Mitutoyo and Mikrocentrum join forces

Mitutoyo, a supplier of geometric measurement tools, and knowledge centre Mikrocentrum have joined forces in the field of industrial measuring technology. This means that as of today measuring technology courses with extensive practical facilities can be held anywhere in the Benelux. For this purpose, Mitutoyo supplies a wide range of measuring tools and samples suitable for mobile use. By pooling knowledge and course material, the quality of the courses has been improved, with a good balance between theory and practice. Mitutoyo feels that general metrology courses are an important service offering and the collaboration with Mikrocentrum allows them to safeguard the continuity of these courses.

WWW.MIKROCENTRUM.NL

WWW.MITUTOYO.NL

"Robotics in health care" theme day

Rising costs in health care and staff shortages in health care institutions have prompted a demand for new medical devices. Interesting developments can already be seen at a number of progressive care institutions and mechatronics companies are not exactly resting on their laurels either. The number of robots/devices used in home care will increase rapidly with, for example, the introduction of a new ISO standard in 2014. Despite the considerable expertise in high-tech systems in the Netherlands, many robotic and mechatronic innovations still originate in Asia.

Under the title "Robotics in health care (a reality rather than science fiction)", Mikrocentrum is organising a theme day on technological developments, the ISO standard and social acceptance. The event will be held on 13 November 2013 at Blixembosch rehabilitation centre in Eindhoven, the Netherlands. In addition to researchers, health care professionals and companies discussing best practices, hands-on experts will have the floor, while a guided tour of Blixembosch is also on the agenda. An important question is that of the acceptance of technology in health care by patients and care providers alike.

WWW.MIKROCENTRUM.NL

NOBLEO TECHNOLOGY – CALL IN THE A-TEAM

Nobleo Technology is a mechatronics knowledge house, founded in 2011 and located in Eindhoven, the heart of the Dutch High-Tech arena. The name Nobleo is derived from “noblesse oblige” and stands for “talent is an obligation”. Nobleo has dedicated tools for talent detection and development at its disposal and believes that it's the engineer's talent that makes the difference in today's high-tech environment of complex and ever accelerating development projects.

Nobleo is a group of highly-skilled and experienced mechatronics professionals operating, for the largest part, on-site and in the heart of the customer's projects, in a role as either consultant, architect, designer or hands-on integrator. By means of coaching and job rotation 'Nobleans' learn fast and create value, for their customers as well as for themselves.

Nobleo provides when it comes to advanced motion systems.

And even though Nobleo is still more or less in its infancy, it has already established a respectable customer base in today's High-Tech arena. Nobleo is recognised by, and cooperating with Philips Lighting, Philips Innovation Services, CCM, TNO, DAF, Mecal, ASML Research, Demcon and others. Nobleo provides when it comes to advanced motion systems for which analytical expertise in the area of system error budgeting, design, (multi-physics) modeling, programming, system integration and experimental validation are required.

Nobleo is a healthy mix of senior and junior profiles within a number of key mechatronics disciplines, such as servo control, system dynamics, actuator design, sensing and embedded software. This mix gives Nobleo's customers (directly or indirectly) access to a large experience base in the field of precision mechatronics.

Nobleo is a strong believer of the V-model of system development. Gaining experience in the right-hand side of the V, the integration phase, is considered a prerequisite before embarking on the left-hand side, architecture

INFORMATION

WWW.NOBLEO.NL



definition and system decomposition. This method of working is applied to projects, be it electronics for LED drivers, high-speed motion systems or 3D printers for chocolates.

Possibly one of the most exciting propositions that Nobleo has to offer is its architect team, a crew of senior technical professionals, who have 'grown' into the role of system architect; they form the A-team and operate in short intensive 'bursts' of a few days. Typically to kick-off a new product, concept or module. As such, Nobleo's customers can literally tap into each other's expertise. Given the industry trend that suppliers are moving from a build-to-print type of services towards integral product ownership à la 'tier 1', the demand for system know-how is ever increasing, and Nobleo helps 'where it counts'. So, why not call in the A-team? ■

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The LiS is founded in 1901 by the famous scientist prof. Kamerlingh Onnes. Nowadays the LiS is a modern school for vocational training on level 4 MBO-BOL. The school encourages establishing projects in close cooperation with contractors and scientific institutes, allowing for high level "real life" work.

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