Proceedings of the Second InternationalWorkshop on
Fundamental Issues and Future Research Directions for Parallel Mechanisms and Manipulators
September 21–22, 2008, Montpellier, France
N. Andreff, O. Company, M. Gouttefarde, S. Krut and F. Pierrot, editors

An adjustable gripper as a reconfigurable robot with a parallel structure

Martin Riedel
Department of Mechanism Theory
and Dynamics of Machines
RWTH Aachen University
Aachen, Germany
riedel@igm.rwth-aachen.de

Marwene Nefzi
Department of Mechanism Theory
and Dynamics of Machines
RWTH Aachen University
Aachen, Germany
nefzi@igm.rwth-aachen.de

Mathias Hüsing
Department of Mechanism Theory
and Dynamics of Machines
RWTH Aachen University
Aachen, Germany
huesing@igm.rwth-aachen.de

Burkhard Corves
Department of Mechanism Theory
and Dynamics of Machines
RWTH Aachen University
Aachen, Germany
corves@igm.rwth-aachen.de

Abstract: In this paper, we propose a robot system, which combines a parallel manipulator with an adjustable gripper. The robot is able to grasp objects with different sizes and shapes without using an additional gripper. It consists of several fingers with contact elements which can be moved independently from each other to grasp the object. After grasping, adhesion forces, provided, e.g. by an electromagnet or a vacuum cup, ensure that the fingertips remain connected to the object to be manipulated. The resulting closed-loop mechanism, formed by the fingers of the robot and the object, features a kinematic structure similar to that of parallel manipulators. The Robot is now able to achieve manipulation of objects with six degrees of freedom by actuating exactly six joints.

Such a parallel robot – gripper combination has many advantages over existing industrial grippers, often used for simple gripping tasks, existing mechanical hands with costly control architecture and parallel manipulators with fixed kinematic parameters.

1. Introduction

The accuracy and the repeatability of manufacturing and assembly processes have to be continuously increased. At the same time, the quality of the processed products and the productivity have to be improved. Hence, manipulators and grippers must always be adapted to the new tasks.

In many automated applications, the handling of grasped objects can be performed by guidance mechanisms or versatile robots that can be customized to achieve different tasks without modifying their architectures or dimensions.

The handling of grasped objects is usually achieved by a gripper, which is a real interface between the robot and the object. Hence, the capability of handling objects with different sizes and shapes depends on the gripper to be used.

Most of the available industrial grippers are conceived to perform simple but special gripping tasks. The use of such grippers, however, has limited functions in terms of versatility and dexterity. In fact, most of the existing industrial grippers in automated installations have to be changed depending on the work piece and on the task, which always causes delay in production and higher costs.

A different way to handle objects in some non industrial applications is the use of mechanical hands in combination with a robot arm. Clearly, these grippers are more versatile, since they are able to enclose the object and to clamp it between the fingertips. Moreover, some of these grippers can be used to position and orient the grasped object. However, a complex control architecture is needed to perform the adequate motion of the fingers. Besides, the accuracy of handling clamped objects is very low.

The use of a handling device is inevitable when larger motion ranges are needed. This can be achieved either by a serial or a parallel robot. In some applications, parallel robots are preferred to serial robots due to their superior kinematic performances. Indeed, parallel mechanisms give the opportunity for the designer to mount all actuators on the base of the mechanical plant. Moreover, closed kinematic chains can be designed in a way that links have to exert only tension or pressure forces. This enhances chances for using a lightweight design that reduces the inertial forces and moments.

Using closed-loop kinematic chains helps improve the end effector's stiffness and the payload of the robot. However, a large number of closed kinematic chains within a mechanical structure can compromise its workspace and kinematic performances in certain configurations.

Inspired by modern grippers and the kinematic structure of parallel robots, we propose a new manipulator that combines the benefits and functions of industrial gripper, mechanical hands and parallel manipulators. This manipulator consists of several fingers, which are capable of connecting their distal links with the object to be manipulated. Unlike existing mechanical hands, the constraints imposed by the connection between the fingers and a grasped object are not frictional constraints. Adhesion forces provided, e.g. by an electromagnet or a vacuum cup, ensure that the fingertips and the object remain connected. These connections have the ability to transmit forces and torques in all directions.

The resulting gripper-object system is a closed-loop mechanism that is similar to parallel kinematic structures. In this case, the number of actuators, required to change the pose (position and orientation) of objects, is equal to the DOF of the gripper-object system. This will be of benefit for the control of the robot – gripper system. Therefore, motion with such a manipulator is more straightforward than manipulation with industrial grippers or existing mechanical hands.

In this paper, we give a short overview of the development and design of the new manipulator.

First, we will abstract some fundamental works concerning the development of our robot. In the following, we present the basic idea and the new concept of manipulation. Then, we will determine the necessary kinematic architecture of the overall manipulator and investigate the structural synthesis of the finger mechanisms.

Finally, we will take a look at the design of the manipulator and the implementation into a prototype and give a short outlook on future projects with this robot.

2. State of the art

Parallel manipulators have been intensively studied and analysed over the last decade. Pioneer works (Gosselin ,1989; Tsai, 2001; Merlet, 2006) pointed out the high kinematic performances of these manipulators and identified their drawbacks. The continuous and intensive research on parallel manipulators has led to a better understanding of these manipulators and, thereby, to better designs that guarantee a dexterous and fine manipulation.

On the other hand, various types of multi-fingered hands have been developed to mimic the dexterity and the grasping behaviour of a human hand. Pioneer designs include the multi-fingered hand designed by Okada (Okada, 1982), the Salisbury hand (Salisbury and Roth, 1983), the Utah-MIT hand (Jacobsen et al., 1986), the Barretthand (Townsend, 2000), the DLR hand (Butterfass et al., 1999) or the University of Bologna Hand (Melchiorri and Vassura, 1992).

Significant efforts have been made to find designs simple enough to be built and controlled, see (Bicchi, 2000). Lee and Tsai developed an atlas of feasible kinematic structures of multi-fingered hands having a mobility number ranging from 3 to 6, see (Lee and Tsai, 2002). The structural synthesis performed there is similar to the structural synthesis of parallel manipulators, see (Tsai, 1999; Merlet, 2006).

Nonetheless, there is a fundamental difference between existing mechanical hands and a parallel manipulator, as pointed out in (Lee and Tsai, 2002). Indeed, the object grasped by a mechanical hand is under force closure, whereas the platform of a parallel manipulator is under form closure, see (Reuleaux, 1963; Bicchi, 1995).

In a general configuration, a parallel manipulator with six degrees of freedom (DOF) can achieve arbitrary position and orientation of the moving platform by actuating six joints (Stewart, 1965). On the other hand, Mason and Salisbury showed that the minimum theoretical number of controlled DOF, thereby the number of actuators, of a mechanical hand to achieve dexterous manipulation is 9 (Mason and Salisbury, 1985). In fact, three fingers are necessary to completely restrain the object in cartesian three-dimensional (3D) space. Moreover, the fingers must track with their fingertips the trajectory of the corresponding contact points on the object, while this is moving in 3D space. Hence, three actuators per finger are strictly necessary.

More precisely, manipulation is achieved, while the fingers constantly have to exert forces on the object to generate cone friction constraints in order not to release it. Manipulation requires, therefore, supplementary actuators to actively control the contact forces between the fingers and the grasped object. Additionally, an adequate control architecture and sensory system are required in order to determine appropriate finger forces for a dexterous manipulation, see (Liu and Le, 2003).

Most of the existing mechanical hands have adopted the concept of force-closure and have some drawbacks, such as complex control architectures due to the high number of actuators and sensors needed to perform delicate tasks. The complexity of dexterous manipulation of objects under force-closure encourages us to rethink this approach.

3. New concept of manipulation

The performances and the range of applications of human hands and industrial grippes often diverge. Our design intends to bridge the gap between the two concepts in order to profit from their advantages and overcome their drawbacks. Hence, our main target is to design a handling device that is multifunctional and can be customized to match the requirements of different tasks. Our design should also be reconfigurable in order to suit the needs of the task. On the other hand, its efficiency and performances should be similar to industrial grippers.
The objective of developing a high-performance and multifunctional handle device encourages us to integrate the object in the mechanical structure of the manipulator.

As mentioned above, the key idea is to generate a closed-loop kinematic chain formed by the robot's fingers and the object similar to the kinematic structure of parallel manipulators, see **Fig 1**. The grasped object and the fingers correspond, respectively, to the moving platform and the legs of a parallel manipulator.

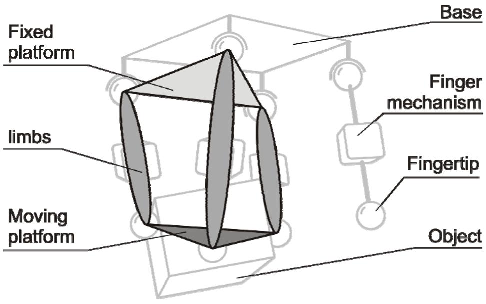

Fig 1: The basic idea:
Analogy with a parallel manipulator

3.1 The grasping phase

Before grasping the object, the fingers are able to position their fingertips independently from each other, see **Fig 2.** The number of actuated joints per finger must be chosen accordingly, e.g. positioning fingertips in 3D space requires three actuators per finger. Hence, objects with different geometric shapes and sizes can be grasped.

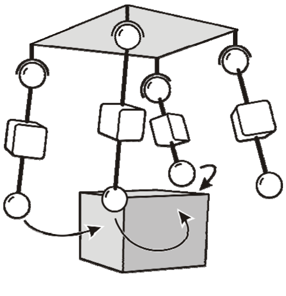

Fig 2: The basic idea:
The grasping phase

3.2 The manipulation phase.

After grasping, the fingers are connected to the object, and the grasped object is now part of a parallel kinematic structure, see **Fig 3**. The appropriate number of constraints imposed by the connection between the fingers and the object depends on the connectivity number of each finger, i.e. the sum of the degrees of freedom in all the joints including the contact point, see (Tsai, 1999). Based on the Grübler criterion, we will show in the next chapter that the connectivity of each finger is a function of the desired mobility number F of the gripper-object system.

It is increasingly apparent that the gripper-object system can be controlled by actuating exactly F joints. The remaining joint positions are determined by the constraints imposed by the actuated joints. Moreover, for a specified position and orientation of the object, we can compute the actuators' positions by solving the inverse kinematics problem.

It should be noted that before grasping the number of actuators can differ from the number of actuators during the manipulation phase. For example, a three-fingered hand has three actuators per finger before the grasping phase, but only two actuators per finger when the fingers grasp and manipulate the object. The remaining actuators are not necessary and can be disconnected or run passively.
Still, their encoders can be used to solve the forward kinematics problem and to determine the actual position of each fingertip. Moreover, the actuators can be used as redundant actuators to overcome singularities or to improve the stiffness and the payload of the mechanism.

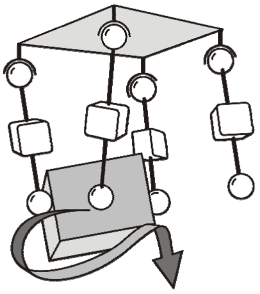

Fig 3: The basic idea:
The manipulation phase

3.3 The reconfiguration phase

A major advantage of a multi-fingered hand is that it can re-grasp objects, e.g. when large rotation angles are needed. We will show in the next section that adding or removing a finger does not affect the mobility number of the gripper-object system, so that re-grasping with the proposed manipulator is also possible, see **Fig. 4**.

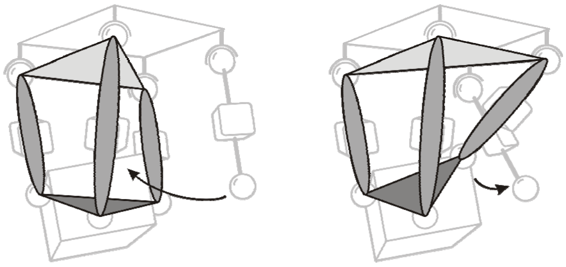

Fig 4: The basic idea:
The reconfiguration phase

3.4 The release phase

After reaching the final configuration, the fingertips are disconnected from the object. The fingers and the object do not form a parallel robot any more. Hence, they can be actuated independently from each other either to move to new gripping points or to rest, see **Fig. 5**.

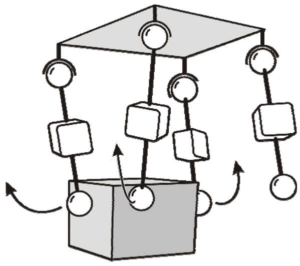

Fig 5: The basic idea:
The release phase

4. Kinematic architecture

Before performing structural synthesis and looking closer at a single finger, we should develop a general concept of kinematic architecture to implement the proposed idea. This involves the determination of the number of fingers, the number of actuators and the contact DOF between the fingers and a grasped object.

4.1 Grübler Criterion

Let n be the number of links, g the number of joints, f_i the degrees of relative motion permitted by joint i, f_{id} the number of identical degrees of freedom in the gripper-object system and λ the DOF of the considered space. According to the Grübler criterion, the DOF value of the gripper-object system F is given by:

$$F = \lambda \cdot (n-1) - \lambda \cdot g + \sum_{i=1}^{g} f_i - f_{id} \qquad (1)$$

Substituting each finger by a unique joint with F_j DOF, we obtain a theoretical mechanism consisting of two links (a grasped object and the gripper's palm) and k joints, where k denotes the number of fingers. Eq (1) can now be written as:

$$F = \sum_{j=1}^{k} F_j - \lambda \cdot k + \lambda \qquad (2)$$

Since all fingers share the same structural topology, we can write,

$$\sum_{j=1}^{k} F_j = k \cdot F_j \qquad (3)$$

Making use of Eq (2), we obtain the connectivity number F_j:

$$F_j = \frac{F - \lambda + \lambda \cdot k}{k} \qquad (4)$$

Substituting $F = 6$ and $\lambda = 6$ into Eq. (4), we obtain:

$$F_j = 6 \qquad (5)$$

Eq. (5) states that the connectivity number of each finger must be equal to 6, regardless of the number of fingers.

4.2 Number of fingers

We distinguish between active fingers, which are in contact with the object to be manipulated and resting fingers, which are not in contact with the object, and can be used for re-grasping.

As seen in chapter 2, only 6 actuators are required to achieve manipulation of the object in 3D space. Consequently, the maximum number of fingers in contact with the object should not exceed six. However, using six fingers leads to a very complex manipulator with more than 18 actuators. For reasons of economy, fingers should also share the same structural topology, i.e. the contact DOF between the finger and the object, the number of joints and the number of actuators. Hence, grippers with four and five active fingers are not considered, since equal distribution of the actuators is not possible. Furthermore, having more resting fingers than active fingers is not adequate.

Table 1 shows all feasible combinations with three active and three resting fingers, where p denotes the number of required actuators per finger for manipulation, q the number of supplementary actuators per finger for grasping and r the total number of actuators. A gripper with only one active finger has limited functions, e.g. unable to provide dexterous and dynamic manipulation. In this paper, the combination 3 active fingers with 1 resting finger is chosen.

	1 resting finger	2 resting fingers	3 resting fingers
1 active finger	$p = 6$; $q = 0$; $r = 12$		
2 active fingers	$p = 3$; $q = 0$; $r = 9$	$p = 3$; $q = 0$; r = 12	
3 active fingers	$p = 2$; $q = 1$, $r = 12$	$p = 2$; $q = 1$; $r = 15$	$p = 2$; $q = 1$; $r = 18$

Table 1: Feasible combinations of active and resting fingers

4.3 Number of actuators in a finger

Each finger should possess three actuators to position its fingertip in 3D space, before grasping the object.

Actually, positioning and orientating fingertips would require a mechanism with 6 actuators. However, this concept would be cost-intensive and is excluded. The first concept can be implemented through the use of passive joints leading to a mechanical adaptation of the fingertip by contact to the shape of the object.

The contact DOF between each finger and the object, i.e. the DOF of the fingertip joints, should be three in rotation, since each finger mechanism should possess three controlled joints. After grasping the object, one actuator in each finger can be disconnected or moves passively.

4.4 Recapitulation

To recapitulate briefly, the constraints, which have to be taken into account prior to the structural synthesis and design of the finger mechanisms, are:

(a) Only six actuators are required for manipulation
(b) The connectivity number of each finger is equal to 6
(c) Three fingers are simultaneously in contact with the object
(d) One finger can be used for re-grasping
(e) Three controlled joints per finger are needed for positioning fingertips
(f) The contact-joint DOF between the finger and the object is 3.

4.5 Structural synthesis

The kinematic structure of each finger should satisfy the conditions developed in section 4.4. The structural synthesis consists now on the one hand in generating finger mechanisms with three DOF and one the other hand in finding joint configurations for the fingertip with three DOF in rotation.

We classify finger mechanisms into three groups according to their topologies: fingers with an open-loop kinematic chain, a closed-loop kinematic chain and a hybrid kinematic chain. Due to the high number of feasible kinematic structures in each group, we define additional constraints to pre-select candidate structures. Finally, we assign these candidate structures values according to weighted evaluation criteria, and chose the most promising kinematic structure, i.e. the structure with the highest score.

The most common topology of fingers in existing mechanical hands is a serial one. This elementary kinematic chain consists of only three links connected by actuated joints. Each actuator can be a revolute or a prismatic one.
Closed-loop kinematic chains feature high stiffness and high accuracy. Yet, they often lead to very complex finger mechanisms with two or three limbs, including three actuated and some passive joints. Due to this number of kinematic chains the whole structure is often limited in its range of motion.
Hybrid kinematic chains with three DOF are made up of a planar closed-loop chain in combination with a single joint in an open-loop arrangement. In a proper configuration they make a good compromise between workspace, stiffness, dynamic behaviour and simplicity.

A small selection of feasible finger structures is show in **Fig 6.**

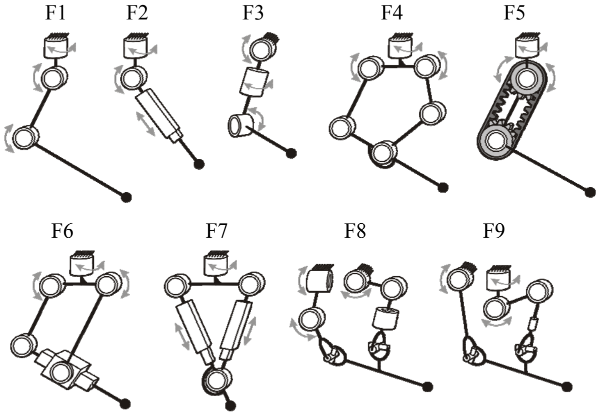

Fig 6: Feasible finger architectures

4.6 Selection

An assessment of the generated finger structures helps to select the most appropriate design solutions, i.e. solution F4 and F5. The kinematic parameters of both solutions can be customized (**Fig. 7**) so that they feature the same workspace.

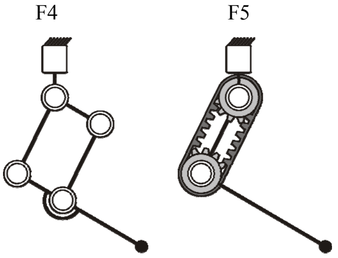

Fig 7: Selected structures with special parameters and identical kinematic performance

The differences between both solutions arise during the implementation of the concepts. Solution F4 meets the requirements concerning small inertia forces and high stiffness better than solution F5.
Fig. 8 shows the selected kinematic structure of the manipulator. It is composed of three five bar mechanisms that are mounted on the base. The supplementary finger is not shown.
The three DOF fingertip joint is designed in a spherical configuration of three revolute joints. This features many advantages, like a large pivoting angle (± 90°) and satisfactory adaptation behaviour during the grasping phase.

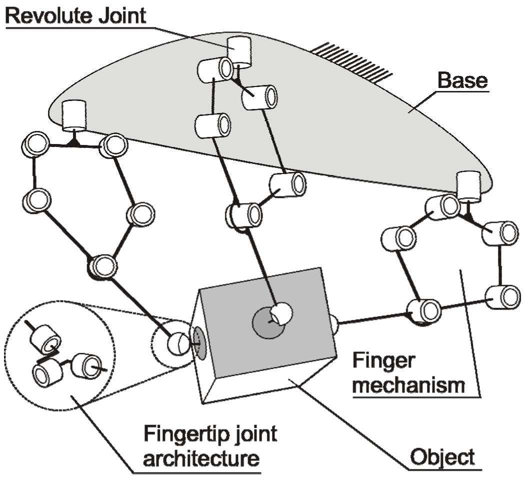

Fig 8: Kinematic structure of the manipulator

5. Design of the prototype

For dimensioning the length of the links and the necessary actuators' features we first define a list of requirements concerning the workspace's volume of the manipulator for a sample object, as well as the maximum allowed values for the size, velocity, acceleration and masses of the objects to be manipulated, see **Table 2**. From this list, we can derive requirements for the finger mechanisms

Requirement	Value
Overall size of the robot	*Maximum:* *1200x1200x1500*mm^3
Geometry of sample object	*Cube:* *150x150x150*mm^3
Desired workspace	*Cube:* *400x400x400*mm^3
Sample manipulation tasks:	
1) PTP Motion *425mm in 0,3s*	*Mass of object: 0.75kg* $v_{max}=1.5m/s$ $a_{max}=15m/s^2$
2) Helix Motion *r=200mm, h=200mm*	*Mass of object: 2.5kg* $v_{max}=1.25m/s$ $a_{max}=8m/s^2$
3) Static Helix Motion *r=200mm, h=200mm*	*Mass of object: 15kg* $v_{max} \ll 1$ $a_{max} \ll 1$

Table 2: List of some main requirements

The optimal dimensioning of the manipulator is an important, but a very complex issue and cannot be discussed in detail in this paper.

We opted for an iterative approach to determine these dimensions. First, we improved the kinematic performances of the manipulator throughout the workspace. Then, we considered a series of different tasks.

It should be noted that the dimensioning of the manipulator is primarily achieved for a sample object.

The validity of the obtained results is checked by computing the workspace and the distribution of the condition number of the manipulator.

Fig. 9 illustrates the shape of the resulting workspace for a constant orientation of a sample object.

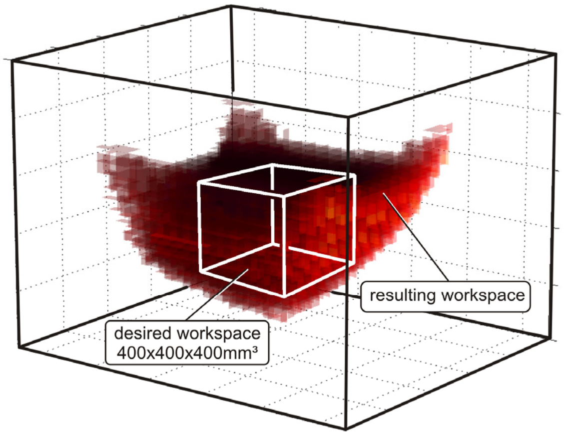

Fig 9: Workspace for a constant orientation of a sample object

Fig. 10 depicts the distribution of the condition number for a given plane of the resulting workspace in a height of 0.5m. The figure shows that the requirement concerning the singularity free condition throughout the workspace is satisfied for this shown slice.

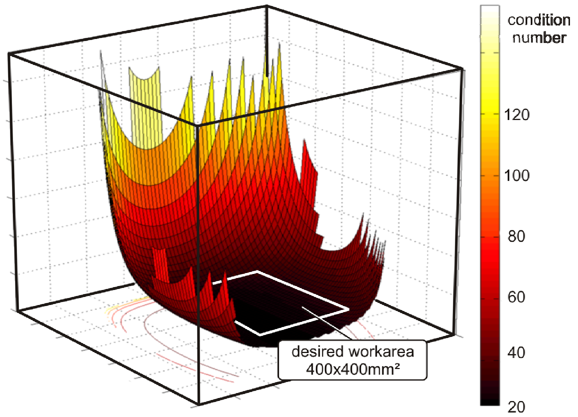

Fig 10: Distribution of the condition number for a slice of the workspace

Moreover, simulations with expected masses of links, joints and other elements of the power train for object motions along given sample paths show that actuators with a nominal rotation speed of 3000 rpm and a nominal torque of 27 Nm meet our requirements.

A gas pressure spring can be used to increase the payload of the manipulator and to reduce the required actuators' forces.

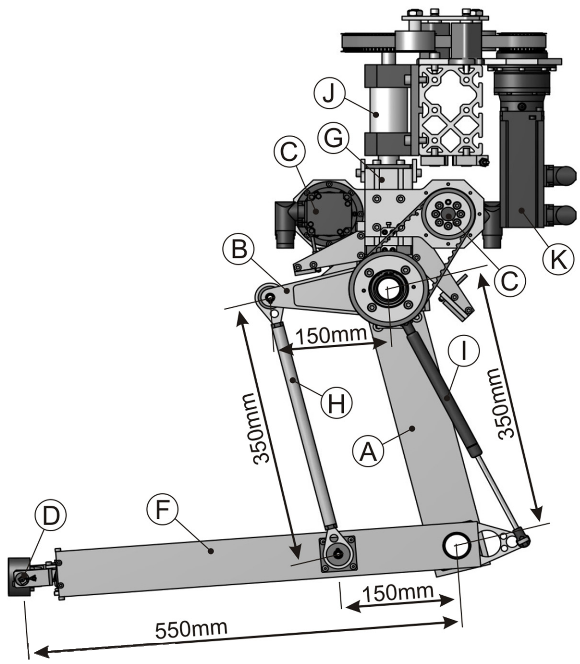

Fig 11: Side-view of one manipulator finger

Fig. 11 shows the implementations of the fingers' concept. Both cranks (A) and (B) are connected with the main actuators (C) via a belt drive. The five bar linkage ensures a controlled motion of the fingertip (D). Forces on the fingertip are carried through the links (F) und (A) and transmitted to rotating frame (G). These links feature a high torsional and bending stiffness thanks to the adequate profile shape. The coupler (H) can be stressed only in longitudinal direction. This enables a lightweight design. A gas pressure spring (I) is mounted between the links (F) and (G) or (F) and (A) in order to unload the actuators and to increase the payload of the manipulator. The whole finger is mounted on the fixed frame adapter (J) and rotates around the vertical axis. The actuator (K) drives each finger to the object to be grasped.

Fig 12 depicts the manipulator with three fingers.

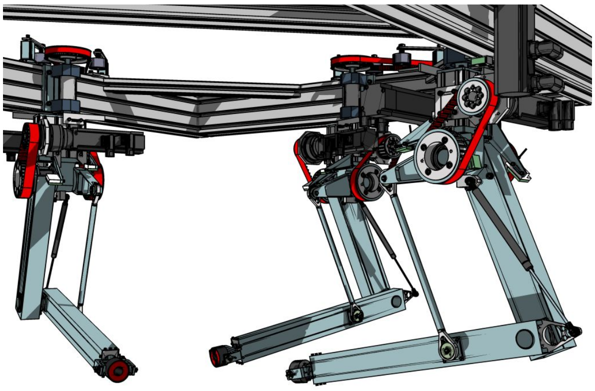

Fig 12: Perspectiv-view of the robot – gripper combination without an object

6. Outlook

The manufacturing of a prototype has already started. Fig. 12 depicts a CAD view of it. Control algorithms are also in the development phase. Once these steps are completed, we will investigate the grasping and the handling behaviour of the manipulator. A 3D optical measurement system will be used to determine the accuracy, the static and the dynamic stiffness of the manipulator.

Moreover, a tool will be developed to achieve an optimal choice of the gripping points for different objects and tasks. We also aim at using image analysis software for detecting the object's configuration. Then, a computation of the optimal gripping points can be performed. This a prerequisite for an autonomous and flexible manufacturing cell.

7. Conclusion

In this paper, we proposed a robot – gripper combination, which is able to grasp different objects and achieve manipulation with six degrees-of-freedom by actuating exactly six joints. The appropriate number of fingers, number of actuators and the contact DOF between the fingers and a grasped object has been determined. The structural synthesis of the finger mechanisms has been investigated. The dimensioning of the gripper has also been discussed. Finally, the simulation results of a manipulation task and a graphical representation of the manipulators workspace have been presented. This robot – gripper combination can be used for industrial applications, e.g. palletization, assembly and sorting as a stand-alone system in a machining centre without being necessarily attached to a guidance mechanism.

6. References

Bicchi, A. (2000). Hands for dexterous manipulation and powerful grasping: A difficult road toward simplicity. *IEEE. Trans. Robot. Automat.,* **vol. 16**, pp. 652-662.

Bicchi, A. (1995). On the Closure Properties of Robotic Grasping. *The Int. Journal of Robotics Research*, **vol. 14**, pp.319-334.

Butterfass, J., M., Grebenstein, H., Liu and G., Hirzinger (2001). DLR II: Next generation of a dexterous robot hand. In: *Proc. IEEE Int. Conf.on Robotics and Automation*, pp.109-120.

Gosselin, C.M. 1988. Kinematic analysis, optimisation and programming of parallel robotic manipulators. Ph.D. Thesis, McGill University. Montreal June 15.

Jacobsen, S.C., E., Iversen, D., Knutti, R., Johnson and K., Biggers (1986). Design of the Utah/MIT dexterous hand. In: *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 1520-1532.

Lee, J.-J. and L.-W., Tsai (2002). Structural Synthesis of Multi-Fingered Hands. *Journal of Mechanical Design*, **vol. 124**, pp.272-276.

Mason. M.T. and J.K., Salisbury (1985). *Robot hands and the mechanics of manipulation*. The MIT Press, USA.

Melchiori, C. and G., Vassura (1992). Mechanical and control features of the UB hand version II. In: *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems.*

Merlet, J.P. (2006). Parallel Robots (Solid Mechanics and Its Applications). Second Edition. Springer, 2006.

Nakamura, Y. and T. Yamzaki (1997). The integration Theory of Reactive Behaviors and Its Application to Reactive Grasp by a Multi-Fingered Hand. Journal of the Robotics Society of Japan, **vol. 15**, pp.136-147

Okada, T. (1982). Computer Control of multijointed finger system for precise object handling. *IEEE Trans. Syst., Man., Cybern.,* **vol. SMC-12**, pp. 289-299.

Reuleaux, F. (1963). *The kinematics of Machinery*. Dover Publications, New York.

Salisbury, K. and B., Roth (1983). Kinematics and force analysis of articulated mechanical hands. *Journal of Mechanisms, Transmission and Automation in Design*, **vol. 135**, pp.35-41.

Stewart , D. (1965). A platform with six degrees of freedom. In: *Proc. of the Institute of Mechanical Engineers*, pp.371-386

Tsai, L.-W. (1999). *Robot Analysis: The Mechanics of Serial and Parallel Manipulators*, Chapter 3. John Wiley & Sons, New York.

Townsend, W. (2000). The barretthand grasper programmably flexible part handling and assembly. *Industrial Robot: An International Journal*, **vol. 3**, pp.181-188

Yoshikawa, T. and K., Nagai (1991). Manipulating and Grasping forces in Manipulation by Multifingered Robot Hands. *Int. J. Robotics and Automation,* **vol. 7**, pp.66-67.