Development of a Self-Adaptive Gripper and Implementation of a Gripping Reflex to Increase the Dynamic Payload Capacity

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Abstract

This paper describes the development of a two finger self-adaptive gripper and the implementation of a gripping reflex to increase the payload-to-weight ratio. The self-adaptive finger mechanism is designed in order to grasp objects with parallel and nonparallel gripping surfaces. The kinematic is optimized to gain a suitable force distribution over the gripping surface to provide a maximum holding torque if objects with parallel gripping surfaces have to be manipulated. Depending on dynamic load affecting the gripped object the proposed grasping reflex increases the grip force to guarantee a stable gripping process. The intention for this implementation is the possible usage of a smaller and thereby lighter motor for a given manipulation problem. Normally the motor is chosen due to the nominal performance which has to cover every use case including the dynamic loads, but mostly these dynamic loads arise only temporarily. Experiments prove the eligibility to increase the performance of a gripping system by using the proposed gripping reflex.

1 Introduction

The main purpose of a gripper is to apply forces and torques at the object which has to be grasped [15]. The stability and reliability of the gripping process depends on parameters such as grip force, adhesion between gripper and object or geometrical fit of the gripper's and the object's contact surfaces. These parameters cannot be optimized for all objects and situations, especially if the design is restricted by weight constrains and space limitations. These restrictions lead to simple lightweight grippers which are however not appropriate in most cases due to the missing possibility to adapt to different shapes [10]. Complex grippers with a high number of actuated Degrees of Freedom (DOF) are complex to control and require a lot of input data. Mechanically self-adaptive mechanism pave the way for the lightweight design of grippers which perform reliable gripping for a wide range of objects without the need for complex control. Weight restriction might appear as a potential problem regarding the mechanical design, but by learning from nature, control strategies become apparent that increase this ratio of payload-to-weight for dynamic cases [7]. This paper presents the overall concept for the **SAmPlInG (Self AdaPtIve Gripper)** system[1], the human inspired grasp-force control and the experiments.

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1.1 Self Adaptive Gripper

Controlling a large number of DOF requires a lot of information to realize even simple grasping tasks [5]. Therefore this concept is not appropriate for industrial cost-efficient uses of a gripper as long as no financial incentive for the automation of complex manipulation tasks arise. This is why grippers for industrial manipulation are in most cases still specialized solutions for single tasks. Due to shortened product development and production time as well as the rising cost of human workers, the need for simple, simultaneously cost-effective and adaptive gripper solutions is existing [6].

Different solutions for self adaptive grippers have been developed in the last decades. The designs differ in the number of actuated and non actuated joints, the coupling of different joints and the way the driving torque is forwarded to these joints. Examples for underactuated hands are given in [14], [3], [10] and [4]. All these grippers have in common that the under-actuation and self adaptation result in a weight reduction and a simple controllable gripper with the capability to grasp various shaped objects. Beside the ability to adapt to different shaped surfaces for the grasping of objects using form closure, the stable grasping of objects with parallel grasping surfaces is a weak point of several of these self adaptive grippers. The reasons therefore are the unstable kinematics and disadvantageous force distributions on the gripping surfaces. This reduces the generated holding torque and the stability is affected negatively while grasping with force closure.

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1.2 Gripping Reflexes

The applied forces and torques are essential for the secure grasping of an object. The required force varies depending on external dynamic forces effecting the object that has to be grasped. Humans vary the used force for grasping depending on the arising external forces and parameters like the friction between object and skin [8] [7]. The safety ratio of provided force and required force has to be minimized in order to reduce physical fatigue and avoid the damage of objects which have to be manipulated [8]. These effects were first studied in the 1980's by Johansson and Westling.

In the last decades these strategies were applied on robotic hands and grippers. This research was mostly focused on the manipulation of fragile objects. Therefore the object has to be grasped with the minimal required gripping force for the static case and this griping force needs to be increased if dynamic loads arise. In [2] the coupling of grip-force and load-force was realized with neuronal networks. These networks are used to initiate the grasp if an object is detected between the fingers, to increase the grasping force if slippage between gripper and object is detected and to influence the manipulator trajectories if a collision between the gripper and the environment is detected. Such human inspired grasping schemes are also realized using classical control architectures [13]. Roman et al. show the results for such an approach with a position and a force controller. The grasping process was divided into six phases, the control software switches the controller depending on the current phase. This switching allows the positioning of the fingers or the control of the grip-force. To realize this the system was equipped with accelerometer, sensors for the finger position and tactile sensor arrays on the fingertips. In [12] the fingers are flexible and equipped with strain gauges to measure the applied force. The forces effecting the object are subdivided into predictable and unpredictable ones. Movements of the manipulator result in planned displacement of the object. This allows the precalculation and generation of force trajectories. The unpredictable forces require a reactive force control which uses accelerometer signals to derive the necessary force to secure the grip. If dynamic forces arise they will influence the object in short time, which is why a reactive grip-force strategy has to be fast to avoid losing control of the object.

2 Mechanical Design

The proposed gripper is designed as a module to be mounted on different manipulators. This requirement led to the choice of actuation with an electric motor instead of hydraulic or pneumatic systems. Furthermore, the needed sensors for object detection, grip-force control and the measurement of forces between the gripper and the manipulator are integrated in the system.

2.1 Components

The SAmPlInG system **(Fig. 1)** consists of two fingers which are actuated by a single motor. The actuator is comprised of a BLDC external rotor motor (Maxon EC flat $45-30W$) and a strain wave gear (Harmonic Drive HFUC-11-100-2A) **(Fig. 2)**. The operating power of this actuator

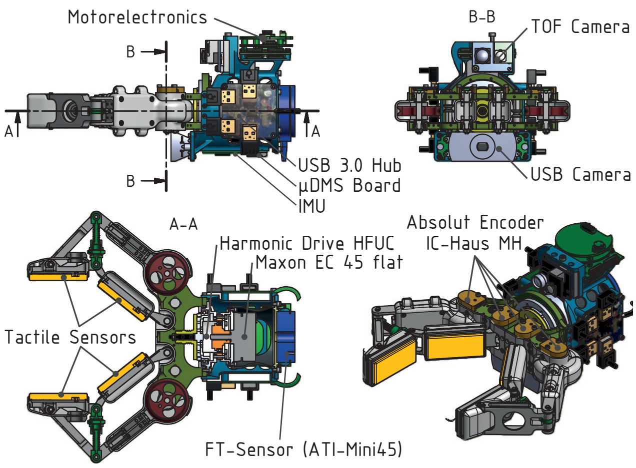

Figure 1 The SAmPlInG system with full setup.

is distributed to the fingers with a tendon-mechanism, substituting heavy levers or spur gears for coupling both fingers and for a further gear reduction. Wire drive mechanisms tend to elastic behavior which is mentioned as drawback of these [10]. This is not controvertible but if the

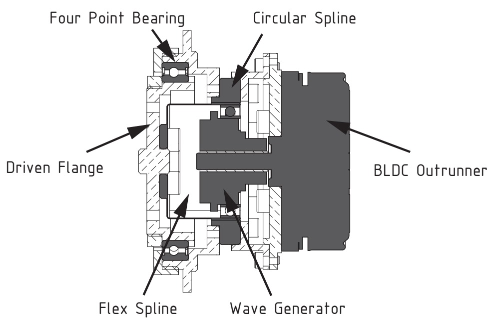

Figure 2 Drive unit to wind up the tendon.

position behind the elasticity is measured the position controller is able to compensate the elasticity and equalize this drawback. It is also alleged that tendon-mechanisms are generally limited to rather small grasping forces [10]. The introduced system provides a nominal grip-force of $40N$ and a maximal grip force of 100 N for a gripper with a mass of $1kg$. These facts in comparison with other grippers prove the general statement about the small grasping forces of wire driven grippers to be wrong **(Tab. 1)**. The gripper is equipped with a Time of Flight (TOF) camera (PMD CamBoard nano) with a resolution of 160 x 120 pixels and a USB Camera (Logitec C 920) with a resolution of 1920 x 1080 pixels to identify objects. The gripping surface is covered by tactile sensor arrays (Weiss Robotics -

WTS 0614-34) each providing 6 *x* 14 sensing points. The two fingers are connected via four pivot joints with the base. Each axis is equipped with a magnetic Hall effect absolute encoder. A force-torque sensor (ATI Mini 45) is used to measure the forces between the gripper and the manipulator. The accelerations, rotations and the magnetic field are measured with an inertial measurement unit (IMU) (Steval MKI121V1 with INEMO-M1). The gripper can be equipped with the **full sensor setup**** or a **basic setup*** **(Tab. 1)**. The information of the tactile sensors and the cameras are

Attribute	Value	Unit
Nominal Power	30	[W]
Grip Force (nominal)	40	[N]
Grip Width	120	[mm]
Angular velocity (nominal)	71,61	$[^\circ/s]$
Weight	1044*/1209**	[g]

Table 1 Gripper specifications.

processed on an external computer while the force-torque sensor data and the position information are processed on the Field Programmable Gate Array (FPGA) (Spartan 6: XC6SLX45) of the motor electronic stack.

2.2 Finger Kinematic

To reduce the number of actuators and provide the required adaptation a self-adaptive mechanism was realized. The proposed kinematic provides a stiff gripping characteristic for objects with parallel gripping surfaces and a self adaptive gripping characteristic for objects with nonparallel surfaces. These requirements result from the objects which had to be manipulated within the DLR SpaceBot Cup 2014 [9]. The gripper was designed for the mobile manipulation platform ARTEMIS [11]. The developed manipulator arm as well as the **SAmPlInG** gripper are now used in human-robot cooperative scenarios [1]. In **Figure 3** the proposed kinematic is depicted (right) beside other self-adaptive kinematics as examples for the state of the art. The proposed kinematic provides a stiff (5) and a adapti-

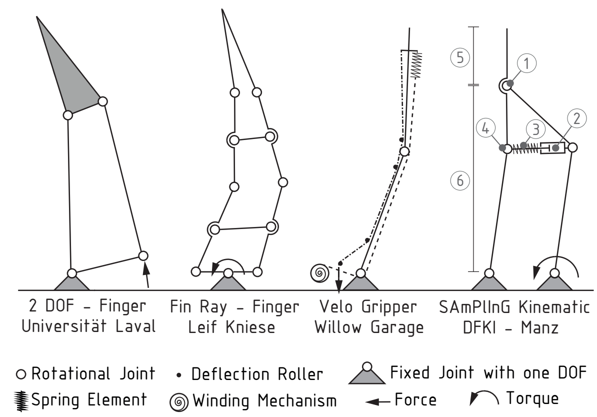

Figure 3 Mechanically self-adaptive mechanisms.

ve gripping zone (6). If an object is gripped in the adaptive gripping zone the spring (3) will be compressed and the gripping surface adapts to the object. The DOF of this adaptive mechanism can be varied to enable the adaptation of more complex shapes if required (**Figure 4**). If objects are

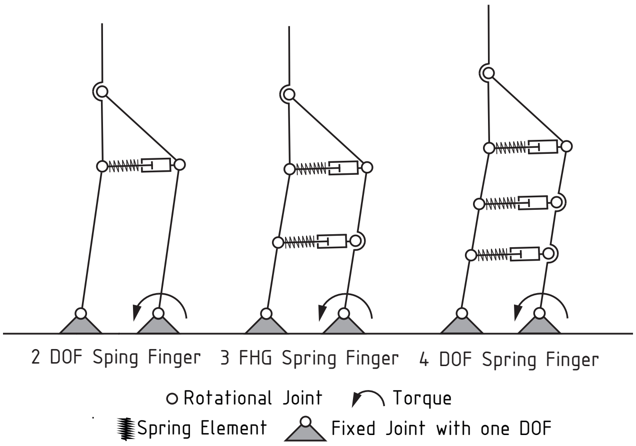

Figure 4 SAmPlInG Kinematics with different number of DOF.

gripped within the stiff gripping zone (5) the piston will be pressed against the stop (2) which keeps the kinematic stiff allowing to precisely manipulate objects with a stiff pinch grip. This design could be used to manipulate small objects as well as objects which are bigger than the gripper and therefore have to grasped outside of the center of mass. In this case the force distribution over the gripping surface is important to prevent the twisting of the object relative to the gripper which is why the kinematic is optimized therefor. To distribute the power of the single actuator to the fingers a tendon-mechanism is used (**Figure 5**). The actua-

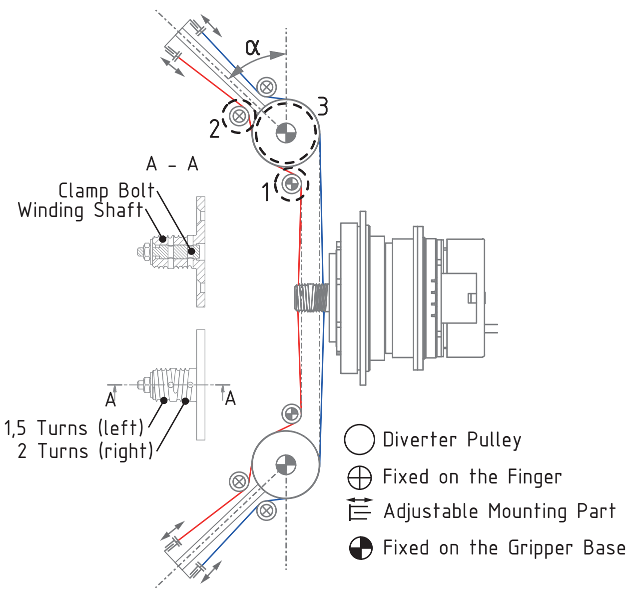

Figure 5 Tendon mechanism for coupling both fingers.

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tor is connected to a winding shaft which has two threads to guide the tendons. These threads are opposed as well as the direction of winded tendons. The winding shaft has two radial holes to feedthrough the tendon coming from one finger going to the opposed one. The clamp bolt inside the winding shaft is used to fix the position if the tendons are positioned. The red tendon is for the closing and the blue one for the opening movement. The tendons could be pre-loaded with the adjustable mounting part in the distal finger segment to keep the tendon drive free of play.

2.3 Simulation

The initial kinematic was determined graphically with the focus on the adjustment to cylindrical objects with a diameter of 80*mm*. Then a CAD model with the identified link dimensions was created and the adaptation to the objects which have to be manipulated within the SpaceBot Cup was simulated with multi-body simulations (MBS) (**Fig. 6**). The optimized kinematic was afterwards

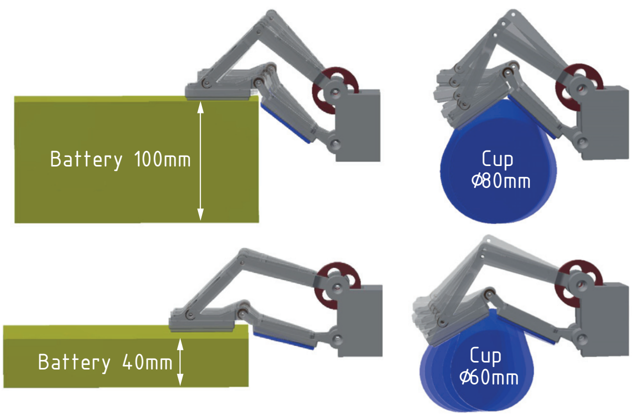

Figure 6 Simulated adaption to the objects.

simulated with non linear mechanical event simulations (MES). After determining the dimensions of the links for a proper distribution the design was optimized and the final part was simulated again to ensure the proper distribution (**Fig. 7**). To minimize the simulation effort only one

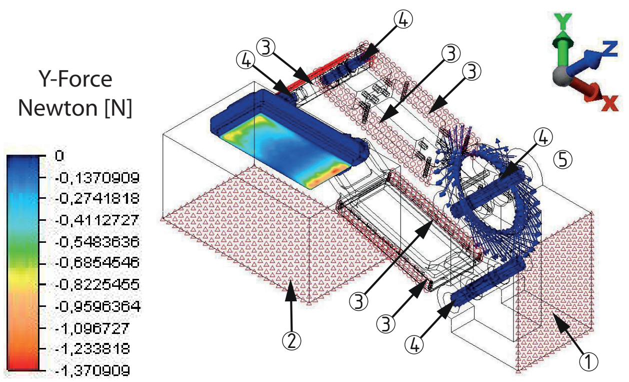

Figure 7 Set up of the Mechanical Event Simulation.

finger was simulated due to the symmetrical boundary conditions. For the simulation the base of the gripper (1) was fixed. The same holds for the lower surface of the cuboid (2) which represent the object which has to be grasped. The links of the finger (3) were locked in Z-direction to reduce the complexity for defining the bearings. All bearings (4) are connected as pin joint types to reduce the computation effort. The generated torque of the tendon drive affects the outer lever of the fingers (5). The results of the simulations are visualized as topological distribution in **Figure 8**.

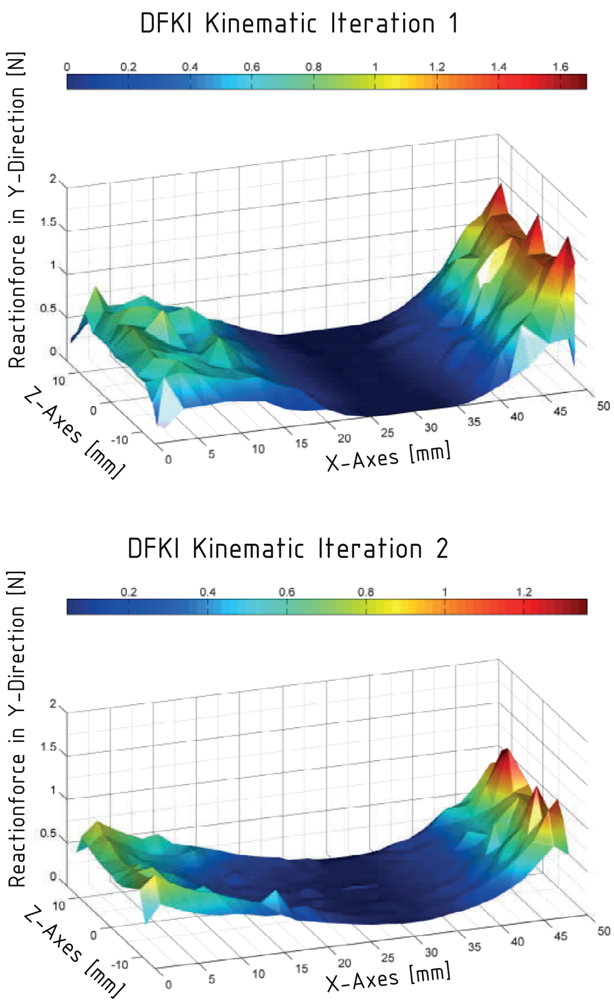

Figure 8 Simulated contact forces.

The overall holding torque is the sum of the forces affecting the finite elements of the contact surface multiplied with the lever length from each element to the weighted average over both dimensions of the surface. This is why the distribution of the forces over the contact surface should be as far off as possible from the weighted average point to generate a maximum holding torque with a given grasping force.

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3 Controller

In the early 1990's physiologists observed and analyzed the coupling of grip-load and applied grip-force of humans while grasping objects in dynamic situations [7]. Humans reduce the applied grip-force to a minimum to grasp the object stable in order to reduce the energy consumption and physical fatigue of the muscles [7]. If dynamic forces arise due to the movement of the human or collisions with the environment the grip-force will be dynamically increased.

This behavior is imitated using a simple control structure with a cascaded controller (red) and a additional servo control (blue) to influence the inner control loop **(Fig. 9)**. The intention for this implementation is the possible usage of a smaller motor for the same manipulation problem. Normally the motor is chosen according to the nominal performance which has to cover every use case including the dynamic loads. The reason for this is that a motor can not be operated over the nominal performance for longer periods. But mostly these dynamic loads arise not permanently but more likely only temporary. This allows the motor to cool down while only static loads exist. The advantage of this struc-

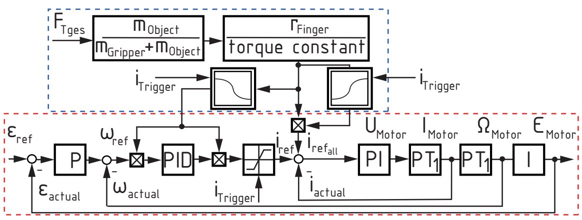

Figure 9 Control scheme with reflex servo control.

ture is the fast response time due to the current controller in the inner loop being directly activated as soon as measured forces rise above the minimum triggering level. The switching function continuously changes from cascaded position, speed and current control to pure current control. The minimum triggering level $i_{Trigger}$ for the switching is determined manually for these experiments. For a practical application this has to be derived for a object by gathering data such as the estimated weight and position of the center of mass. The reason for using a simple current control to adjust the grip force is the expected rapid response. The stiffer the fingers are, the faster the rising of the grip force will be. This is one reason why the indirect control of the grip-force by controlling the finger position tends to be slower. The first implementation for prototyping was realized on a *MicroAutoBox II (MABX II)* from *dSpace Systems*. This approach allowed a rapid control prototyping without considering the FPGA computation capacity in the first experiments. The MABX II calculates the required voltage as controller output which is send to the motor electronic stack. This voltage is then generated by the motor electronic stack using pulse-width modulation (PWM). The measuered sensor signals are filtered on the electronic stack and then send to the MABX II as input for the controller. This controller is realized in *Matlab Simulink*™ and compiled for the MABX II **(Fig. 10)**.To use the considered structure for the gripper the optimal controller had to be designed. Therefor the step-response of each control loop

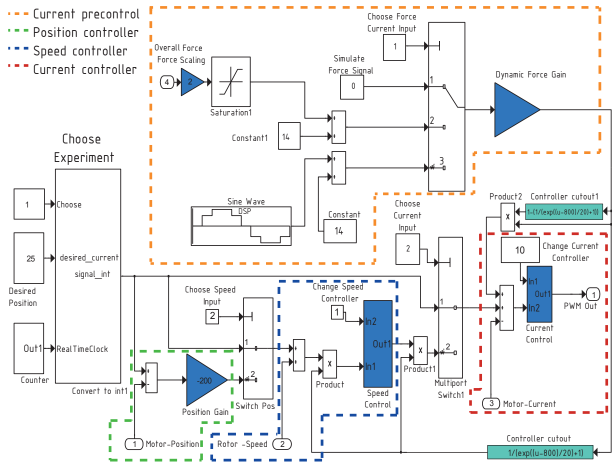

Figure 10 Matlab Simulink impementation of the control structure.

was recorded and the model identified with the *MathWorks System Identification Toolbox*™. Then a controller for each control loop was designed using the *Control Design Toolbox*™.

4 Experiments

The first experiment with the proposed controller concerned the evaluation of the dynamic adaptation for a sinusoidal test signal **Figure 11**. The current (grip-force) remains at $i_{Trigger} = 800mA$ which is the determined current for the manipulation in the static load case. This parameter

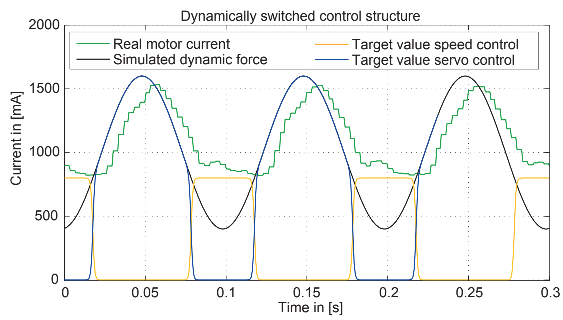

Figure 11 Dynamic switching from cascaded position control to force-based control.

depends on the weight of the object to be grasped and other boundary conditions which have to be known a priori or estimated by the robot. If dynamic forces between gripper and manipulator arise the current will be increased in approximately $0.01s$ to hold the object in position. This fast adaptation time for the grip-force is the major advantage of the proposed approach in comparison to other solutions.

These experiments were carried out to analyze the switching from position control to current (force) control and vice versa. To validate the gasping reflex in realistic situations an acceleration test bench was used to apply dynamic loads on the gripper while grasping an object (**Fig. 12**). The

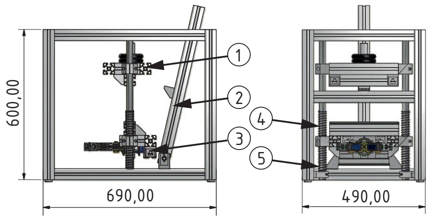

Figure 12 CAD model of the test bench.

test bench consist of two sliding carriages, the upper one (1) is loaded with weights, the gripper is mounted on the lower one (3). Between the two sliding carriages and under the lower one are springs (4 & 5) to cushion the impact. The upper sliding carriage is held by a bar (2) to arrest the position and ensure repeatable conditions. The springs can be used to change the excitation frequency and the combination with the variable weights and the adjustable stopper at the bar allows to adjust the acceleration as well. For the experiments an acceleration of $3g \equiv 29.43\ m/s^2$ and a excitation frequency of $5.5Hz$ was appointed. **(Figure 13)** shows the experimental set up during the release of the dynamic load. The current for the static case has to be

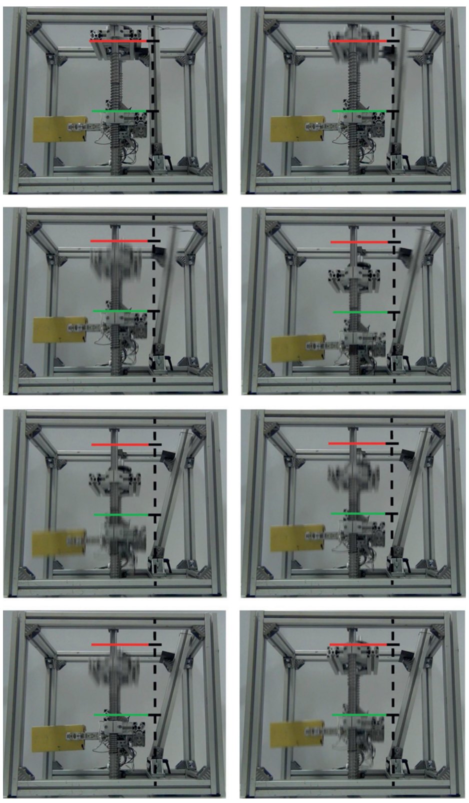

Figure 13 Experiment sequence with the grasped object.

$800mA \equiv 35.55N$ for the given object. To hold the object under dynamic conditions a current of $1500mA \equiv 71.27N$ is necessary. Without the gripping reflex the gripper had to be powered constantly with $1500mA$ to prevent the objects rotation relative to the gripper. **Figure 14** shows the results measured during the experiment. The experiment indicate

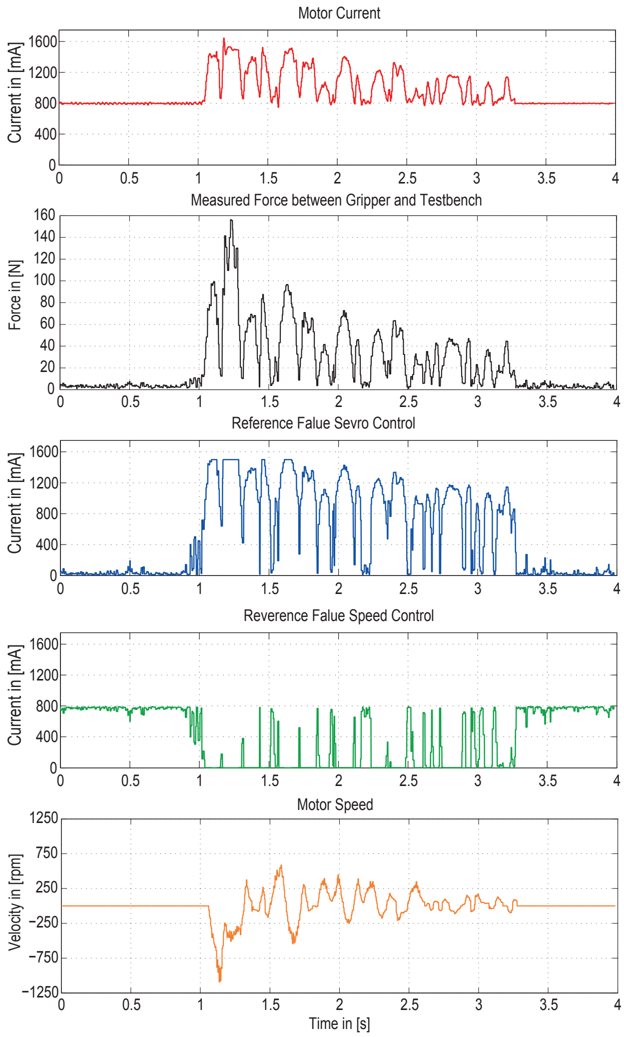

Figure 14 Results for the dynamic load experiment.

that the energy consumption can be reduced with a gripping reflex while the manipulated object is grasped in a stable manner even if dynamic forces arise in short time.

5 Conclusion and Future Work

The proposed kinematic exhibit an extended adaptability for grasping objects with nonparallel gripping surfaces. This self adaptive kinematic reduces the complexity of controlling the gripper and establishing a secure grasp. Furthermore, the kinematics provide a suitable force distribution over the gripping surface to handle objects with parallel gripping surfaces and generate a large holding torque.

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Weight and payload of a gripper are crucial properties for manipulation, especially for mobile robots. The introduced control scheme mimics the human grip-load force coupling and allows to grip an object with minimum force in static cases and to increase the gripping force if dynamic forces arise. These characteristics allow the design of lighter grippers using smaller motors.

In the future we will investigate the possibilities to increase the performance of the gripping reflex by using other sensor information. Beside the force information we want to estimate the orientation of the hand with the IMU and use this knowledge to estimate how gravity affects the gripped object. To improve the usability we plan to measure the mass of the object which has to be grasped in an initial step with the FT-Sensor to calibrate the minimum trigger level.

6 Literature

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