

Design of a Mechanical Gripper with an Integrated Smart Sensor Network for Multi-Axial Force Sensing and Perception of Environment

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1. Introduction

The dynamic process of grasping different kinds of objects which are pressure sensitive is difficult to handle with classical feedback controllers based on few force sensor values acquired and processed outside of the gripper structure. Side effects like slipping can not be detected at all or too late. Miniaturized smart sensors embedded in structures like grippers can significantly increase the perception of the environment with which a structure interacts.

A high-density network of strain-gauge sensors distributed in/on the gripper structure providing local sensor signal-to-information computation can deliver much more suitable information.

Traditionally, strain-gauge sensors are used to measure an applied force in a specific direction. The analog signal acquisition is difficult due to low noise immunity of weak input signals. External signal acquisition with a large distance from sensor to electronics raises noise and reduces signal-to-noise ratio and resolution.

We propose and demonstrate the integration of an active smart sensor network into a mechanical gripper structure (finger). The network consists of several highly miniaturized low-power sensor nodes providing sensor signal acquisition, data processing, and communication. Each sensor node can handle up to two strain-gauge sensors detecting different forces at different positions of the gripper structure. The relation between strain and force is derived from FEM simulation of the gripper structure under certain

load conditions.

Each node performs sensor signal acquisition using a zooming ADC approach, sensor data evaluation, and auto-calibration. Hence, non-calibrated and non-long term-stable sensors can be integrated and used, a prerequisite for robust sensorial materials.

It can be demonstrated that an integrated sensor network leads to increasing functionality and robustness.

A smart communication protocol is used to provide robust and fault-tolerant communication between nodes and an external interface, for example, a generic processor-based controller.

Beside the collection of single force values measured at different positions of the gripper, temporal and spatial composition information derived from the set of measured forces can be computed using data fusion, performed by the nodes of the sensor network itself using distributed computing algorithms. These are overload conditions, force gradients, object recognition and classification, and other higher-level information which can be computed.

A multi-agent system is used for a decentralized and self-organizing approach of data processing in a distributed system like a sensor network, enabling the mapping of distributed data sets to related information required for object manipulation.

2. Gripper Structure, Sensor Network, and Communication

Mechanical grippers are key components of handling devices in automated assembly systems. For complex handling tasks, these grippers have to be equipped with additional force-measuring modules. The proposed gripper fingers, based on previous work in [2], contain six single-force sensors and can measure forces along multiple axes.

Each sensor is connected to an active sensor node consisting of signal and data processing, communication modules, and power regulation. Each sensor node can connect with neighbour nodes (up to four links).

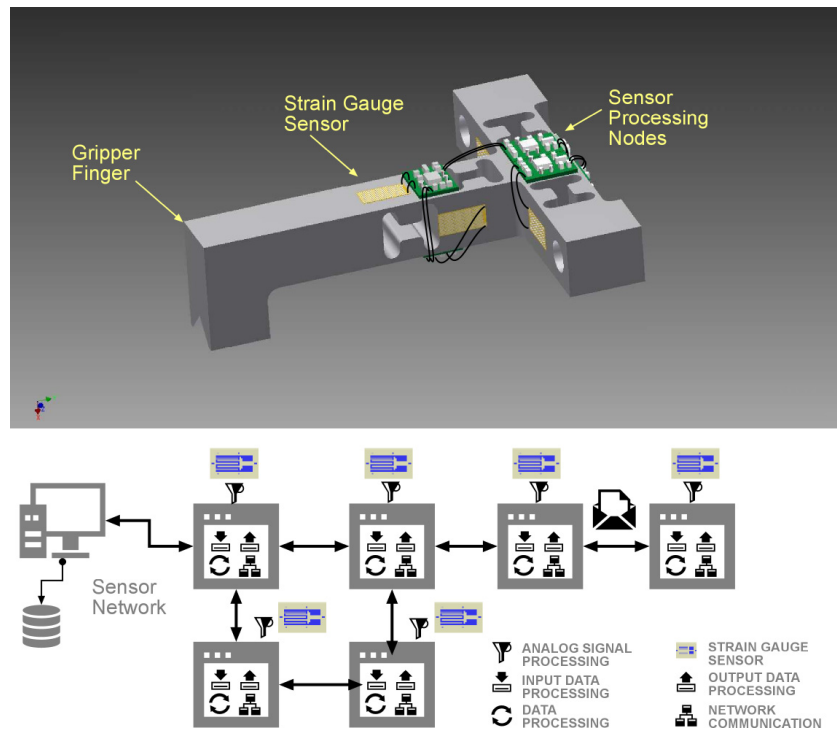
Communication uses the **Simple Local Intranet Protocol [3]** featuring:

- message-based point-to-point communication
- protocol is scalable: network topology, network size, data size
- no unique node addressing, instead delta distance vector addressing in

Cartesian coordinates (1- to n-dimensional)

- simple and **smart routing strategies**, required for irregular/incomplete network topologies, reliability, and robustness against link failures
- available both in software & hardware implementation targeting FPGA/ASIC technologies and SoC-Design

Fig. 1. One gripper finger equipped with a sensor network connecting nodes each servicing a strain gauge sensor mounted on the gripper structure. The network topology is shown in the lower part (mech. structure based on [2]).



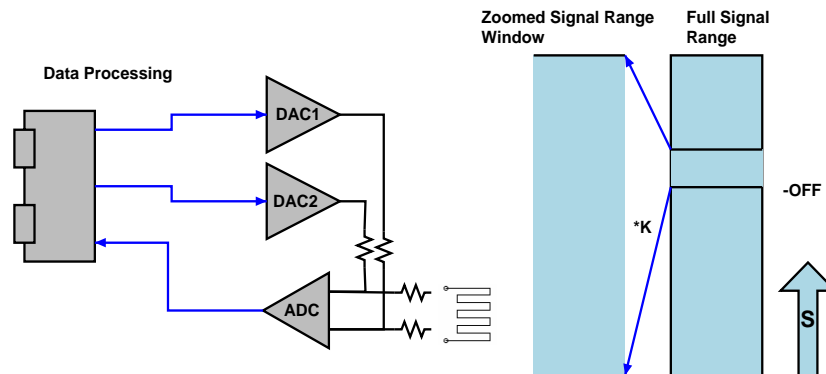
3. Sensor Signal Processing: ZOOM-ADC

Resistive sensors, like strain-gauge sensors, provide only a small relative change in resistance in the order of 1% resulting from a change of applied load in the considered operating range of the sensor. Using bridge configuration, providing a differential signal, require compensated sensors with small tolerances in strain and zero-load resistance parameters, actually not applicable to sensorial materials using, for example, printed sensors.

Assuming only one uncalibrated and uncompensated resistive sensor, a zooming window approach (see eq. 1) can be used to match an initially unknown sensor to the measurement system preserving a high and full-range

resolution, shown in figure 2.

Fig. 2. Zooming ADC system architecture used for signal acquisition of resistive sensors with high relative sensitivity and auto-calibration. (ADC: Analog-to-Digital Converter with differential input, DAC: Digital-to-Analog Converter)



The data processing performs an initial (or periodically repeating) auto-calibration finding the center of the operational window by using fast settling successive approximation, shown in algorithm 1.

Eq. 1. Window transformation of signal s (zooming in region of interest)

$$W(s) = k(s - off)$$

Alg. 1. Autocalibration using successive approximation

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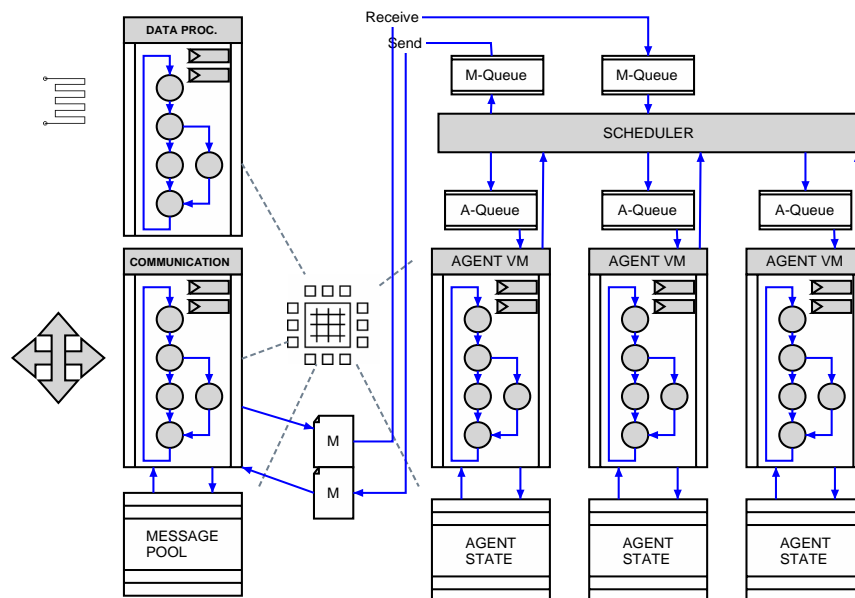
1 sar ← DIGITALRANGE/2;
2 DAC1 ← GAIN0, DAC2 ← 0;
3 WHILE sar <> 0 do begin
4   IF ADC > DIGITALRANGE/2
5     THEN DAC2 ← DAC2 + sar ELSE DAC2 ← DAC2 - sar;
6   sar ← shift_right(sar,1); end;
7 off ← DAC2-DAC1;
```

4. Distributed Data Processing with Agents

Initially, the sensor network is a collection of independent computing nodes. Interaction between nodes is required to manage and distribute data and computed information. One common interaction model is the mobile agent. An agent is capable of autonomous action in an environment with the goal to meet its delegated objectives. An agent is a data processing system, a program executed on a computer system, that is situated in this environment [1]. A multi-agent system is a collection of loosely coupled autonomous agents migrating through the network using a message-passing system providing mobility.

The state of an agent is completely kept in the message transferred in the network, but not the functional behaviour. Figure 3 shows the proposed execution environment used for the data processing agents. There is a message module implementing delta-distance routing, and several finite-state-machines implementing the agent behaviours and providing virtual machines able to process incoming agents. All parts are mappable to digital logic on RTL and SoC system architecture, a prerequisite for miniaturized sensor nodes embedded in structures and sensorial materials. Preliminary tests and a prototype show the suitability for a smart sensing gripper.

Fig. 3. Sensor node building blocks providing mobility and processing of multi-agent systems: parallel agent virtual machines, agent-processing scheduler, communication, and data processing. All parts are mappable to digital logic on RTL and SoC system architecture.



5. References

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