Copyright IEEE: ISBN:978-1-5090-6545-5. Mechatronics and Machine Vision in Practice, 21-23rd November 2017

Requirements for a Cloud-based Control System Interacting with Soft Bodies

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***Abstract*—Interaction with non-rigid objects poses a challenge for manufacturing systems. The dimensions, locations and physical properties of soft-tissue objects like fruit or meat are subject to considerable variation and uncertainty. Possible ways to accommodate this are to use a number of different types of sensors and actors. However, a control system physically located next to a manufacturing system is often limited in terms of computational power and flexibility. New or different sensors are difficult to integrate, and the processing of their data cannot be accomplished in a feasible time.**

In the wake of Industry 4.0, cloud-based control emerged, which may provide a solution for the above-mentioned situations. A cloud environment provides hardware and software resources that allow for fast processing. The support of different programming languages and frameworks reduces development effort.

This paper examines challenges for robots in the two application areas of high-value crop harvesting and meat processing and derives requirements for control systems interacting with soft-tissue.

***Index Terms*—Agricultural engineering, Computer vision, Control systems, Cyber-physical systems, Manipulators, Robot control**

I. Introduction

Soft-tissue robotics deal with the handling of soft materials and workpieces [1]. Emerging applications related to production are found in the agricultural sector [2]: high-value crop harvesting [3], [4] and meat processing [5]–[8]. Automation in these areas is desirable due to costly labour or a strenuous working environment. The main differences and their arising challenges compared to conventional engineering are ill-defined dimensions and locations of the workpieces, variation of their physical properties and fragility.

Possible solutions to deal with these challenges are machine vision, advanced sensing, specialised actuators and innovative algorithms [3], [4]. Each of these components creates or processes large amounts of data.

Classical control systems, located next to the machine, have limited computational capacity [9]. The data cannot be processed extensively enough while respecting timing requirements at the same time. Connectivity and software environment are often limited as well. This lack of support for different programming techniques, languages and frameworks is a hindrance for developers.

In the wake of Industry 4.0, cloud-based control emerged, which provides a solution to the above-mentioned problems [9]. A cloud environment provides hardware and software resources that allow for fast processing of data from various sensors and actors [10]. Ease of access through the cloud offers improved maintenance [9]. The support of different programming languages, techniques and frameworks reduces development effort [11].

This paper will examine the differences, challenges and tools of soft-tissue robotics in the areas of high-value crop harvesting and meat processing (Section II). It will evaluate whether a cloud-based control system can offer advantages over a conventional control system (Section III). Requirements for a possible control system will be derived (Section IV) and discussed (Section V). The goal is to provide guidelines and advice for the subsequent development of successful cloud-based control systems for soft-tissue robotics and related manufacturing systems.

This research is part of the International Research Training Group (IRTG) project "Soft Tissue Robotics" jointly undertaken by the University of Auckland and the University of Stuttgart.

II. Challenges in soft-tissue robotics

The exact location and orientation of soft-tissue objects is often unknown. For some applications, e.g. orchard harvesting, even the presence of these objects must be first discovered. This fundamentally differs from conventional engineering where rigid bodies can be expected to fall within a narrow scope of their specified properties.

Table I lists characteristics of the two reviewed application areas.

A. High-value crop harvesting

Bac et al. [3] reviewed harvesting robots of the past 30 years. While some achieved functionality within a narrow scope of specific conditions overall, none achieved commercialisation. It identified that the main challenges for successful robot operation in this area are variations of crops and production environment. Further recommendations for future research and development were given, for example addressing the lack of consistent performance measurement methods.

A similar review with a sole focus on machine vision was performed by Kapach et al. [4]. It states that machine vision

TABLE I
CHARACTERISTICS OF APPLICATION AREAS

	High-value crop harvesting	Meat processing
Key challenges	• Variation within a crop • Variation within a production environment • Variation between crops	• Variation between stock • Variation between breed • Variation within season • Interaction between tool and meat
Tasks	• Locate fruit • Asses ripeness • Trajectory planning and collision detection • Cut off and collect fruit	• Measure anatomy • Trajectory planning • Gripping • Cutting • Collecting
Technologies	• Machine vision • Specialised robotic arms and end-effectors • Robotic platform • Adaptive algorithms	• Machine vision • Food-grade robotic arms • Specialised grippers • Adaptive algorithms
Constraints	• Minimise damage to surrounding plants • Sturdiness against water, wind and dirt • Process monitoring	• Track and trace • Food-grade hygiene

is a key technology for further automation in agriculture. The ever-changing lighting and environment make this a difficult task. Downstream applications of machine vision in quality control were described by Davies [12].

Emerging possible new sensors are hyperspectral cameras. A pixel of the acquired image contains intensity values for multiple bins within a wavelength band. Conventional cameras only capture a single or three values per pixel for black & white or colour photography respectively. However, hyperspectral imaging is costly regarding price, acquisition and processing time [4], [12]. The current use is limited to offline model creation and research [4].

Lien [13] talks about the limitations of conventional pinch grippers in food handling. Some fruit is easily bruised.

B. Meat processing

Robots are already commonly used for food packaging [7]. Introduction of automation in further upstream processes, i.e. slaughtering, selecting and butchering, still faces economic and technical challenges. Automation can only be successful if it surpasses manual labour in productivity [5], [13].

The key challenge for an automation system to achieve high efficiency and productivity is the biological variation by species, breed or even season [14]. The animal parts must be properly gripped, fixed and cut. In order to achieve this the animal's anatomy has to be properly measured [8]. A skilled worker can respond to these variations based on his senses (visual and haptic) and experience [7]. As mentioned by [13], conventional pinch grippers are insufficient for this task due to the meat deforming and slipping out of the grip.

Reference [6] positions the development of new sensors and control systems as the main enabler for automation in the meat industry. The incorporation of different sensor technologies (including machine vision, CT scanning and force-feedback) and the subsequent trajectory planning are necessary however not easy tasks [8], [15].

Due to high legal demand for hygiene and quality control the traceability of meat products is an important aspect [16]. Possible methods are the application of special markers to the meat itself or ensuring that the material handling system can account for the origin of each cut of meat [17].

III. COMMON TASKS AND TECHNOLOGIES, AND ADVANTAGES OF A CLOUD-BASED CONTROL SYSTEM

This section aims to identify common tasks, technologies and constraints within the two application areas (see table II) and examines possible benefits of a cloud-based control system.

As stated earlier, ill-defined workpieces pose the biggest challenge. The main technology to introduce ability and intelligence to cope with this challenge is machine vision. Ideally, it will provide an accurate three-dimensional model of the measured objects and its surrounding. Machine vision requires innovative algorithms and high processing speeds. A cloud-environment can greatly facilitate development and use of such algorithms. The programs do not need to be tailored to run on specific embedded hardware, and computational power in the cloud enables real-time execution despite copious amounts of data (e.g. use of hyperspectral imaging) and novel adaptive algorithms. Adaptive algorithms are proposed to deal with the variations in soft-tissue robotics [3], [4], [8]. An example is the utilisation of artificial neural networks or genetic algorithms. Both require extensive or distributed computational power [18]–[20].

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Once targets and surroundings have been successfully measured, trajectory planning can be carried out. Trajectory planning is a complex and challenging task. Three-dimensional kinematics, collision detection and multiple constraints create the need for innovative algorithms. The same benefits as for machine vision algorithms apply.

Another aspect is the gripping and the use of tools by the robot. As some of the workpieces are fragile or lacking structural integrity, innovative grippers are necessary. Improvements can happen in the mechanical design of the gripper, through the addition of (force-)sensors, or both. This also applies to other tools like knives or cutters, used to slice meat, cut carcasses or cut off crops. [13] mentioned anthropomorphic grippers as a possible solution. However, their high cost poses an economic barrier. Anthropomorphic grippers are the subject of extensive research [21]–[23]. Their use will require integration of numerous sensors and novel actuators [22] into a possible control system. A flexible cloud-environment can aid with the development.

In addition to these main functions, analytics and traceability are desired or necessary: in crop harvesting for performance analytics, and in meat processing for legally required safety standards. In a cloud-based control system the data of the system's components is already present, thus facilitating subsequent process monitoring and analysis greatly. Additional distributed sensors and devices for tracking can be easily integrated.

TABLE II
COMMON CHARACTERISTICS OF APPLICATION AREAS

Tasks	Technologies	Constraints
• Identification of target • Location of target • Trajectory planning • Movement execution and adjustment	• Machine vision • Robotic arms • Robotic end-effectors • Adaptive algorithms	• Adaptability • Monitoring

IV. DERIVED REQUIREMENTS FOR A CLOUD-BASED CONTROL SYSTEM

Based on the reviewed challenges, the common tasks and tools, and possible benefits requirements have been derived. They can be grouped into three categories: connection, computational power and usability.

Additionally, the components to which the individual requirements mainly apply are listed.

A. Connection

A cloud-based control system requires a permanent remote connection. Therefore its main requirements are related to the connection itself.

- Timing - A control system needs to react to certain signals in real-time, i.e. respond within a specified (short) time-frame and with low jitter. This is certainly true for motion control loops that can even become unstable if the delay reaches a threshold [24]. For systems communicating over longer distances this creates a challenge. Each node within the network infrastructure contributes to signal delay and jitter.

  Components concerned: local network infrastructure, cloud

- Bandwidth - Machine vision and advanced sensing are becoming a key aspect in future automation. Due to new technologies (e.g. multispectral imaging) and an expected increase in their numbers, the amount of data is likely to grow in the future. The different tiers of nodes within the network infrastructure need to provide sufficient bandwidth to cope with these amounts of data.

  Components concerned: local network infrastructure, cloud

- Connectivity - A component directly connected to a cloud-based control system requires network connectivity. Components need to be fitted with additional interfaces and communication capabilities. Sockets or wireless routers need to be within range. Alternatively, mobile radio communication can be used, which is an option for outdoor applications. It should be kept in mind that remote areas might lack mobile radio coverage and that metallic obstacles and enclosures can obscure radio signals.

  Components concerned: local network infrastructure, local hardware, control system

- Safety - Safety needs to be inherent to any technical system. This poses a challenge in a networked environment that relies on permanent connectivity. In any case of connectivity loss, the manufacturing system or its individual components need to ensure the continued and save execution of pre-transmitted instructions or a save shutdown.

  Components concerned: local hardware

B. Computational power

The next group of requirements is related to computational power.

- Infrastructure - A single (personal) computer will not be able to perform the anticipated amount of computations in real-time. In a cloud environment with numerous CPUs and cores the physical resources are virtualised and can be provided on an on-demand basis to ensure sufficient computational power. This is referred to as Infrastructure as a Service (IaaS) [25].

  Components concerned: cloud

- Algorithm scalability - The infrastructure provides increased computational power through scalable numbers of cores. For sufficient computational power an application, i.e. the control system, needs be able to use the infrastructure's scalability. To achieve this the developed algorithms of the control system and its subcomponents need the be implemented for parallel execution.

  Components concerned: control system

C. Usability

With increasing servitization throughout industries, the classical distinction between developer and user becomes increasingly difficult to make. A more apt view is that every party offers services while consuming other services. Tools are not only developed for end-users but also for other developers that reuse many existing solutions. In this context (re-)usability becomes a key aspect.

- Standardised interface - The effort of connecting a plethora of different hardware and software components will be greatly reduced when they provide a simple unified interface. OPC UA has often been coined as the new standard of Industry 4.0 [26]. A known preceding design principle is Service-Oriented-Architecture (SOA).

  Components concerned: control system

- Platform-independence - Developers prefer different software tools and programming languages for different purposes. Supporting a free choice of tools greatly facilitates development. Programming frameworks are increasingly developed or optimised for cross-platform compatibility (e.g. Python, Qt, .NET Core). Cloud providers naturally understand this need and offer services coined Platform as a Service (PaaS) [11]. It enables developers to focus more on their code without worrying about the underlying frameworks and infrastructure.

  Components concerned: cloud environment

- Adaptability - Not only during development but also after deployment the individual components of a cloud-based control system should be easily interchangeable or modifiable. Conditions in a soft-tissue manufacturing environment can change and quick adaption is necessary. The operator should not have to rely on third-party experts to make small changes.

  Components concerned: control system

V. Discussion

Commercial solutions from big vendors (e.g. Amazon, Google, Microsoft) already fulfil most of the demands for the cloud environment, including IaaS and PaaS. Recently GPUs and FPGAs became available in the cloud, offering further improvement in computation time and efficiency for specific algorithms. However, [27] and [28] identified timing as a challenge yet to overcome: A machine tool whose control system was moved into the cloud was subject to frequent stoppage due to delayed or lost data packets. Reference [29] used Industrial Ethernet and stayed within the local network in order to circumvented delay due to connection and to focus on the examination of the delay introduced by a cloud-based PLC itself. Industrial Ethernet enables deterministic real-time communication but requires specialised hardware and cannot connect to the internet.

Bandwidth and timing are a challenge both for the cloud infrastructure and the local infrastructure. Within the local network the traffic will be high, and if a cloud provider in the internet is chosen, additionally the ISP needs to provide a sufficient connection to and within the Wide Area Network. The latter aspect is often out of the hands of individual manufacturers and its upgrade requires investments from telecommunication providers. Hopes are placed on the currently developed Time Sensitive Networking (TSN) standard [30]–[32]. Until its completion and implementation interim solutions need to be found. [9] provides further reference points.

Given the current state of things, it is advised to chose a cloud provider in close geographical proximity or set up a local-cloud environment which satisfies the requirements.

An important aspect, and a main idea of the Industry 4.0 movement [26], [33], is a unified interface or communication standard. With different vendors offering different systems, this is a key requirement to ensure compatibility within a connected environment. The OPC UA standard takes into account many different industries and allows for specialised components and provides modelling guidelines [34]. Changeability and scalability of a control system will greatly benefit from this unification allowing the modularisation of subcomponents. Parameters could be easily adjusted through the afore mentioned interface but also a complete replacement would be easier. Vendors need to ensure to follow these guidelines.

Algorithms that require big amounts of computational power are usually developed with parallelisation in mind. Research in computer vision, neural networks, machine learning is extensive and subsequently developed tools offer an easy way to incorporate the technology into applications. A competitive cloud-environment offers adequate development tools (PaaS).

VI. Conclusion

Two agricultural application areas of soft-tissue robotics were examined. The key characteristics and challenges of these fields were collected. Common traits among these were identified. Requirements for a cloud based control system were derived.

The main challenges for a cloud-based control system will be related to the connection between components and the cloud, and the establishment of common standards.

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