How Fluid Power Research Can Contribute to a More Sustainable Construction Industry

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Abstract

The construction industry is facing severe challenges in near future. The reasons are widespread. First, the growing earth population leads to a continuously rising demand for infrastructure, living and industrial space, forcing the construction industry to raise productivity. On the other hand, the building and construction sector is responsible for approx. 34 % of the global anthropogenic CO_2 emissions, while this share will grow further with enhanced construction activity. Significant parts of these emissions result from the production of building materials. Cement production alone generates approx. 6 % of the global emissions, due to its enormous used quantities and high temperature requirements in production. Paradigm changes in raw material selection, building designs, and material use are therefore unavoidable. Additionally, the drive systems of mobile construction machines contribute to the sector's emissions. While construction principles need to change, the requirement for earth moving and mining and thus for more efficient and emission-free working machines persists. Finally, construction is a labor-intensive branch, facing severe problems with recruitment due to the shrinking number of young people in many industrialized countries and the direct concurrence with more attractive, less physically demanding jobs.

The paper shows how fluid power can contribute to an ecologically and socially more sustainable construction industry by means of several examples from current research at ifas and beyond. Herein, both dimensions of sustainability are simultaneously optimized by automation of construction processes, e.g. by means of partly automated mobile machines with additional intelligence, to allow real time surveillance of the building progress, fluid power enabled automated prefabrication of lightweight assemblies, which require less concrete and labor on site, and enhanced switching schemes and fluid selection for mobile hydraulics to ensure increased energetic efficiencies.

Keywords. Fluid Power Research, Construction Industry, Sustainability.

1. INTRODUCTION

The world is facing a strongly growing population, which is forecasted to peak only in the year 2084 with 10.3 billion people living on earth [1]. This implies that over the next 60 years, living space, production facilities, transportation, etc. need to grow by approx. 25 % of the existing infrastructure only to maintain the current average standard of living. Meanwhile, the global birth rate had its maximum already mid of the last decade and is shrinking [1], which will lead to a significantly reduced number of young craftsmen in a few decades in many countries. Ultimately, higher demands on productivity, automation, and reduced manual workload in construction result. This is especially the case for China, Europe, India, and Japan while persistent population growth, and thus a stable number of workers is forecasted for the United States over the century [1].

In parallel, the limitation of climate change, which is attributed by most scientists and governments to the anthropogenic greenhouse gas emissions, results in higher demands, awareness, and legislative restrictions on these emissions. Starting with the UN conference in Stockholm 1972, possible pathways to minimize greenhouse gas emissions aiming to limit climate change to a temperature increase of 1.5 °C above pre-industrial levels end of the century have been discussed. With the Paris Agreement, a binding international treaty was achieved in 2015, which paves a way to the temperature goal by defining quantitative reductions in greenhouse gas emissions over time to achieve net zero emissions in 2050. Meanwhile, recent studies show, that despite huge efforts to reduce greenhouse gas emissions, economic growth has offset these reductions and emissions still not declined. Peak emissions are forecasted for the current period and a temperature increase of 2 °C will probably result. [2]

The combined challenges of construction industry resulting from fast-growing population, which requires intensive construction activities, reduced availability of workers, demanding for highest productivity and automation, and limitations in greenhouse gas emissions, can only be addressed by innovative solutions on all involved fields of research. Therefore, a comprehensive understanding of sustainability is required, not only including closed material cycles and strongly reduced climate gas emissions during production and service life but also the social and demographic dimension.

In the following, the role of fluid power to solve the before mentioned challenges in construction industry is discussed.

2. CLIMATE IMPACT AND FUTURE OF CONSTRUCTION INDUSTRY

In 2024, the building and construction sector accounted for about 34 % of global energy-related CO_2 emissions [3]. In addition to building operations, such as heating, ventilation, air conditioning, and lighting, the production of raw materials and the operation of construction sites are significant drivers of carbon emissions in this sector. Furthermore, the sector's immense resource consumption negatively impacts its sustainability.

In 2024, 3,950 Mt of cement were produced [4]. Including emissions from associated industrial processes, cement production accounted for 2,324 of 38,153 Mt total CO_2 emissions in this year, corresponding to a share of 6.1 % [4]. Approx. 60 % of these emissions are attributed to the heated limestone, while the remaining 40 % is linked to the operation of the cement kiln and other production processes [5]. While global net-zero emissions are targeted by 2050, cement demand is projected to reach 3,535 Mt accounting for only 48 Mt of CO_2 emissions for this year, as shown in Figure 2.1 [4]. A significant reduction in CO_2 emissions from production is therefore necessary: from 588.4 kg of CO_2 per ton of cement in 2024 to 13.6 kg of CO_2/t in 2050 to achieve global net-zero emissions.

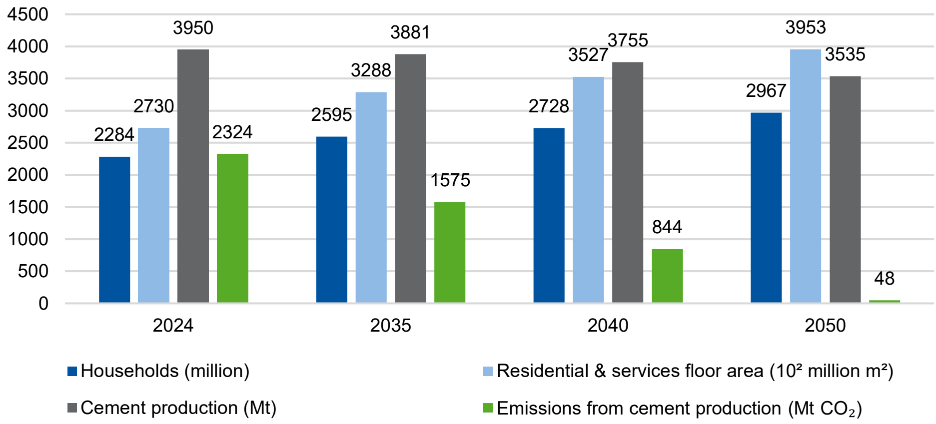

Figure 2.1. Trends in household and residential & services floor area demand compared with cement production and correlated CO_2 emissions, based on actual values (2024) and targets of the 'Net-Zero Emissions by 2050' scenario [4]

To reach this goal, while maintaining or even improving performance, the proportion of Portland clinker must be reduced or substituted with lower-emission materials [5]. Emissions can be further reduced by implementing process-related changes, such as improving energy efficiency and operating the cement kiln with hydrogen or electricity.

In addition to cement, steel is an important raw material for the construction sector. Although not all the steel produced worldwide – 1,883 Mt accounting for 2,750 Mt of CO_2 emissions in 2024 – is used in the construction sector, this resource still contributes significantly to the industry's emissions [4]. Additionally, approx. 400 Mt of CO_2 emissions were produced by mobile hydraulic machinery in the construction sector in 2022, corresponding to approx. 1 % of total CO_2 emissions [6].

Consequently, the climate targets in the 'Net-Zero Emissions by 2050' scenario can only be achieved through higher design and construction efficiency (approx. 22 % of the total contribution) as well as low-emission materials and manufacturing processes (approx. 31 % of the total contribution). Additional measures, such as carbon capture during cement production, are also necessary [5].

It is obvious that switching hydraulic construction machinery from combustion engines to hydrogen or battery power alone is insufficient. Additional measures on machine side are required for economic and social viability. Selected pathways and their potential are discussed in the following chapter 3. Furthermore, novel automation approaches to raise productivity in construction and to allow usage of emerging material-minimized construction methods, e.g. carbon-reinforced concrete (CRC), partly rely on fluid power drives and are discussed in chapter 4.

3. FLUID POWER RESEARCH FOR EFFICIENT MOBILE MACHINES

Most mobile working machines used in construction are driven by one central prime mover. This can either be an internal combustion engine or an electric motor for battery electric systems. The supplied power is transferred by one or several hydraulic pumps to a valve control system, which distributes the power and controls the multiple actuators by throttling. Especially the parallel movement of multiple actuators with significantly deviating load pressures poses a challenge concerning efficiency for conventional systems if the pressures cannot be decoupled by using separate pumps for the active drives. Meanwhile, several studies show that trained excavator operators use multiple drives simultaneously over a significant share of the operational time [7], which leads usually to a mismatch between available number of pumps, their flow capability, and the required motions even on heavy machines with several main pumps. Therefore, state-of-the-art valve systems are generally not built to drive each actuator with a single pump. Furthermore, state-of-the-art switching schemes do not allow for energy recuperation and generate extensive throttling losses to control assistive loads, e.g. during deceleration of the swing or boom down of an excavator.

In contrast to former products, the ongoing electrification of mobile working machines has the potential to realize emission free operation, if clean electric energy is assumed, which is targeted for 2050 [2]. The Chinese market for such machines is worldwide the first rapidly growing, while wheel loaders are the driving component [8]. To allow for cost and material effective machines with reasonable battery capacity and sufficient operation time between charging cycles at a time, efficiency is even more relevant for battery electric systems than for conventional ones.

As efficiency is increasingly important and the highest optimization potential lies on system level, most research activities concerning mobile hydraulic efficiency optimization of the last decades have focused on concepts to decouple the load pressures of different parallel used drives and to allow for energy recuperation. Consequently, different approaches have emerged:

At ifas for example, the STEAM architecture, which consists of a multi-pressure rail system with accumulator buffered quasi constant pressure rails, allowing for load adaptive selection of the driving and counteracting pressures on conventional cylinders, has been developed and tested. While its energy savings attributed to reduced hydraulic throttling losses stayed reasonable, huge improvements in overall efficiency have been achieved by its quasi-ideal loading of the ICE and pump. For three representative work cycles, efficiency increase of 27 % to 32 % has been achieved in comparison to a conventional load-sensing machine [9].

A second widely discussed approach is the usage of hydraulic multi-chamber cylinders, which are supplied by at least two constant pressure rails [10]. The fundamental concept is comparable to the multi pressure rail systems but differs in switching constant pressure on variable cylinder chambers instead of variable pressures on constant surfaces. Industrialization of this concept is pursued by companies *Norrhydro and Volvo*, claiming up to 50 % reduction in fuel consumption on an excavator [11]. Of course, combinations of these two approaches can be found in literature. A recent example, which considers three pressure rails and multiple three chamber cylinders, predicts efficiency increases of 22.3 % to 36 % in comparison to a state-of-the-art system [12].

Another approach to the same technical problem is the usage of hydraulic transformers to adapt the pressure from a constant pressure rail to the loading condition of the connected cylinder. Generally, these transformers consist of two coupled displacement units with at least one variable displacement to adjust pressures. Therewith, throttling losses can be omitted and power transferred in both directions, allowing for recuperation of cylinder power into the supply line and connected accumulators. Due to the high number of required displacement units, a highly integrated transformer design with improved efficiency and noise emissions is key. Significant achievements in this field have been realized by *Peter Achten* [13]. Simulated efficiency increases of the hydraulic system of an excavator using hydraulic transformers in comparison to its conventional counterpart are forecasted to be as high as 31 % [14]. Meanwhile, additional efficiency increase of the machine due to optimal loading of the prime mover was neglected in this study, showing even higher potential in general.

Another approach considers the direct displacement control of all actuators by a set of variable displacement machines, which are driven by one common prime mover. While it allows avoidance of control valves and associated losses, additional measures need to be taken to allow for energy recuperation, as the recuperated energy on the pump and prime mover shaft needs to be stored somehow. *Hippalgaonkar and Ivantysynova* have shown that for a 5 t mini excavator, the fuel consumption could be cut by half and thus efficiency doubled by pure displacement control with recuperation capability [15]. Efficiency gains for bigger machines, which have usually more efficient baseline hydraulics, will be probably lower while for realization, pump losses and investment costs are the main challenges, as the overall installed displacement volume of the machine must be significantly higher than for its conventional counterpart to achieve comparable performance.

A possible approach to reduce displacement volume and cost of the installed units has recently been proposed by *Schmidt and van Binsbergen-Galán*. By connecting two chambers from two different working cylinders, this connection and the two remaining ports can be controlled in pressure and/or flow by means of displacement units. The performed statical analysis forecasts a reduction in overall displacement volume of up to 36 % in comparison to a conventional displacement-controlled approach. [16]

If electrified machines are investigated, electro-hydrostatic actuators (EHA) with separate electric drives for all actuators are an option. A reduction in pump displacements is achieved by using fast rotating electric machines. Furthermore, the implementation of variable speed motors allows fixed displacement pumps to be used, e.g. internal gear pumps, to cut system costs [17]. The control of such EHA with required load-holding capability requires complex control algorithms, which have been widely researched [18]. Nevertheless, building space and cost constraints prohibit realization of pure electro-hydrostatically actuated serial machines to date.

A hybrid approach proposed by *Mu, Cheng, and Tang*, which consists of a conventional load-sensing system with only one cylinder, which is replaced by a four-chamber cylinder, to act in parallel as LS-cylinder and EHA, has shown to be an interesting and simple to implement alternative. In a case study for a battery electric 6 t excavator, this measure reduces energy consumption by 15.6 % with an EHA power rating of 7 kW. [19]

Another possible solution proposed by *Sah and Li*, consists of a multi pressure rail system, which is combined with small electro-hydrostatic units for each actuator to adjust pressure and flow to the required level. Therewith, the installed electrical power can be drastically reduced in comparison to EHA-driven machines, which means lower investments in electric motors and frequency converters, while the pump displacements of the controlling units stay comparatively large, as each unit needs to be sized for full actuator flow. [20]

In conclusion, despite many studies and realized full-size prototypes, hydraulic architectures with significantly improved efficiency are still waiting to come on the market. Different studies demonstrate that less than 50 % of the mechanical power of the prime mover shaft is transferred into working power [15, 21]. The different proposed system architectures, allowing for recuperation, reduced throttling losses, and optimal loading of the prime mover, and the achieved experimental efficiencies suggest that there is potential to cut power demand of existing machines by half. Unfortunately, costs, building space, robustness, and maintenance aspects are still hindering broader application of these approaches, especially for machines with internal combustion engines.

Meanwhile, the changed cost structure of battery electric systems makes efficiency measures economically more attractive, as battery capacity can be reduced for a more efficient system to achieve the same time of operation. Higher efficiencies also positively impact the product carbon footprint of the battery electric machines, the raw materials needed, and operational costs, while electrified machines are the most promising way to reach the greenhouse gas emission goals, under the condition that clean electric energy is available.

Hydrogen powered solutions are probably going to exist in parallel for remote environments without sufficient grid connection. Also in this case, hydraulic system efficiency is from utmost importance, as highly compressed or liquified hydrogen will stay resource demanding in production and therefore an expensive energy carrier. By using fuel cells, achievements in the field of battery electric systems can directly be applied to the hydrogen powered counterparts.

Ongoing research in this field, taking the specific possibilities of electrification into account, is forecasted to significantly improve sustainability and to allow for higher degrees in automation of mobile construction machines over the next two decades.

In contrast to the above-mentioned energy saving methods on system level, automation of construction machines is already ongoing in the market. Grade assist functions for excavators, which allow for assisted surface leveling, slope grading, or trenching and enable measuring the weight of the moved soil can be purchased as an option on selected recent machines. As a result, the process is accelerated and the operator's workload is reduced in parallel, while also less experienced operators are enabled to perform the task. Generally, for safety reasons, the operator still needs to command the machine, even if this command is reduced to continuous lever deflection to enable automatic motion. [22, 23]

Contrary to this, the company *Liebherr* showed recently a fully autonomous wheel loader for repetitive tasks, e.g. to repeatedly load hoppers or move goods from A to B [24]. Of course, this system is still very limited in comparison to the usual working tasks of some construction machines, e.g. wheeled excavators, but it represents a first step in the required direction and further, more challenging demonstrators are awaited.

Another possibility to reduce the physical load on the operator is teleoperation of mobile machines. This allows the operator to sit in a calm and warm cabin or office, while the excavator is performing its task outside. This can lead to significant risk mitigation in selected work environments, e.g. in demolition. Required components and software tools are already widely existent, thus enabling prototypical realizations. *Gerdes et al.* evaluated different visualization techniques for teleoperation and came to the result that stereoscopic visual feedback with a camera mimicking the operator's head movements is best suited. Main challenges are the user perception of the machine's motion, the awareness for the surroundings, and cyber security. [25]

This overview shows that current research and development in the field of fluid power is paving the way for an ecologically and socially more sustainable generation of mobile machinery. Meanwhile, novel opportunities for fluid power to explore new markets are created from the already ongoing transformation of the construction industry itself. In particular, the automation of manually dominated tasks, which is necessary to achieve greater productivity given the shrinking number of skilled workers, holds great potential.

4. Novel Construction Principles Involving Fluid Power

The following section focuses on advanced approaches to automated formwork systems as an exemplary emerging technology in the construction sector that utilizes fluid power. A recent example with significantly improved productivity and safety is the PERI VARIOKIT Composite Track (VCT) system, which is shown in Figure 4.1. This system aims to build steel composite bridges faster and with higher quality. Therefore, the formwork is attached to a slide, which is supported by the bridges steel girder under the concrete slab and hydraulically moved to allow sequential buildup of the in-situ concrete carriageway slab. The slide is automatically moved along the entire bridge length by means of hydraulic cylinders using the pilgrim step method. The hydraulic drive mechanism, which threads through the anchors on the steel girder and manoeuvres the entire formwork to its intended location, is shown on the right in Figure 4.1. [26] Further examples are found in the field of automated climbing systems for high rise buildings and bridge posts, as e.g. the DOKA super climber system, which moves the formwork by one story at a time and assures its correct orientation by means of a set of hydraulic cylinders [27].

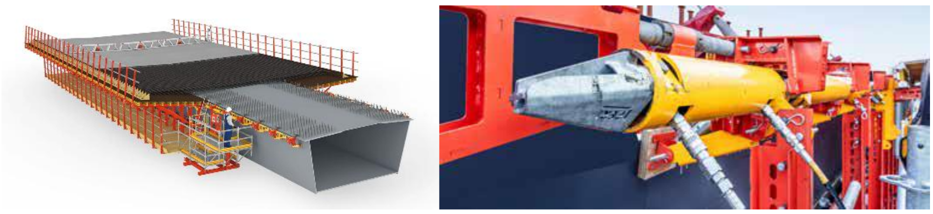

Figure 4.1. Automated formworks – PERI VARIOKIT Composite Track [26]

Besides more sustainable construction machines and higher productivity through automation, lower emissions and raw material usage associated with higher mechanical performance of the structural components are required to achieve sustainability goals in construction industry. One possible solution to meet these demands is to use innovative, sustainable materials, and tailored construction principles, which allow for industrialized prefabrication and fast assembly. Associated research in construction engineering has therefore the potential to open new fields of application for fluid power systems, especially to automate prefabrication plants and on-site assembly.

This is where the research of the Collaborative Research Centre/Transregio 280 (CRC/TRR 280), involving researchers from TUD Dresden University of Technology, RWTH Aachen University, Leibniz Institute of Polymer Research Dresden, University of Hamburg, and TU Darmstadt, comes into play. The overarching goal of this research consortium is to develop innovative design strategies for material-minimized CRC structures to establish sustainable principles for a new approach to construction. [28–30]

The investigated carbon reinforcements consist of multiple endless fibers impregnated with a matrix resin to form bars or sheets. Due to the lower density and higher tensile strength than steel, smaller reinforcement cross-sections are possible, as shown in Figure 4.2. In addition to its use in renovating existing structures, such as residential buildings, industrial facilities, and bridges, CRC particularly demonstrates its full potential in new construction in the form of thin-walled, lightweight, and high-strength structural elements [28–31]. [32]

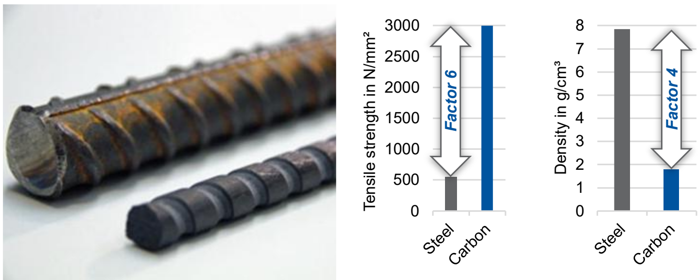

Figure 4.2. Carbon vs. steel reinforcement [32]

A further key advantage lies in the corrosion resistance of carbon fibers. Consequently, corrosion-related damage is prevented, resulting in longer lifetime for CRC and reduced maintenance costs. Additionally, the concrete cover can be reduced to the minimum required for structural stability, resulting in significant material savings. Depending on the application, concrete consumption can be reduced by up to 80 %. At the same time, CO_2-minimized binders can be used, which is significantly more complex for steel reinforcement due to oxidation issues [33]. These savings directly translate to manufacturing, transportation, installation, demolition, and recycling and positively impact economic efficiency and sustainability of the entire construction sector. [32]

Exploiting the full potential of CRC leads to significantly minimized material and volume, and thus to delicate construction designs. However, these material-minimized structural elements have very low stiffness in a flat or simply curved state. Therefore, they are not suitable for load-bearing installations, e.g. in ceiling structures, without additional measures. This is why new construction strategies and associated manufacturing methods are investigated.

A novel design strategy to achieve sufficient rigidity of these elements is to incorporate fold lines. This creates high local stiffness, resulting in a significantly higher load-bearing capacity. The strategy is inspired by classical origami and uses waterbomb tessellation. Therewith, material is used only where loads are transferred. In this way, loads up to 45 times the module's own weight can be carried. Many of these modules can be combined and assembled into large-scale structures by exploiting the periodicity of the waterbomb tessellation, as shown in Figure 4.3; however, strict manufacturing tolerances must be maintained to evenly distribute loads in the structure. [34–36]

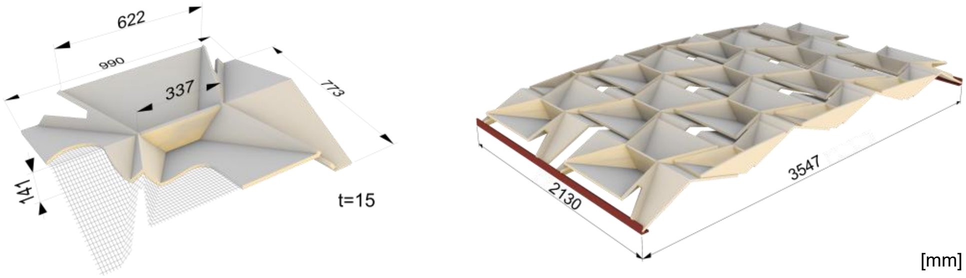

Figure 4.3. Waterbomb tessellated module and assembly [36]

These geometrically complex modules cannot be efficiently manufactured using conventional methods, such as lamination, casting, or injection molding [32]. The "fold-in-fresh" methodology represents a novel, efficient manufacturing process that is applicable to concrete in green state with soft or freshly impregnated carbon reinforcement [37]. In this process, the modules are folded from a flat, planar state into the desired final geometry using a folding tool that replicates the desired shape. The modules then cure inside the tool. Thus, this method enables a customized yet sustainable manufacturing process. [36]

The initial prototype of this folding tool was developed at ifas in cooperation with the Institute of Structural Concrete at RWTH Aachen University. The tool consists of a foldable surface that is actuated by pneumatic cylinders via a gear mechanism. The tool surface is composed of a continuous, flexible, fiber-reinforced plastic membrane, which is locally stiffened by steel facets in accordance with the waterbomb geometry. Thus, only the membrane is present in the narrow gaps between the facets, serving both as a folding joint and as a seal against the concrete matrix. Actuation causes a spatial displacement and tilting of the facets, resulting in a continuous transition from the flat, planar state into the folded structure of the final component.

Although folding a waterbomb cell theoretically involves only one degree of freedom, the soft characteristics of the membrane-based fold-lines allows flexing of the structure and thus deviations from the exact waterbomb geometry. On the one hand, this compensates for manufacturing and assembly inaccuracies throughout the entire tool, ensuring that the tool surface folds easily and no jamming occurs. On the other hand, however, to ensure defined movement of the facets and unique tool geometry in the folded state, flexing must be minimized. In the first demonstrator, this is achieved by mechanical synchronization and guidance of some degrees of freedom of the folding tool. Synchronization is achieved by implementation of a mechanically synchronized motion of two parallel linear guides, which hold the bearings of the outer facets to exploit the symmetrical properties of the waterbomb geometry. This mechanism is located beneath the tool surface and is directly actuated by five pneumatic cylinders to evenly distribute the driving force on the system and thus to avoid jamming. Meanwhile, to avoid excessive loads on the membrane joints, two additional cylinders are attached to the bearings of the inner facets, which hold the majority of concrete weight during folding due to their dominating surface. Thus, in sum, seven force-controlled pneumatic actuators, which are pneumatically interconnected in three symmetrical groups, are used to evenly actuate the folding tool and allow for smooth movement.

Despite the resulting kinematic overdetermination, the system does not jam thanks to the elasticity of the membrane and pneumatic actuators. Smooth motion is achieved through a combination of throttles and time-based pressure control, which provides drive-group-specific, time-varying force. For a detailed description of the initial prototype of the folding tool, as shown in Figure 4.4, see *Bhat et al.* [38]. Besides the required force control, pneumatic actuation has been selected for its outstanding robustness and simple maintenance in the dusty and harsh environment of a construction laboratory and later industrial usage.

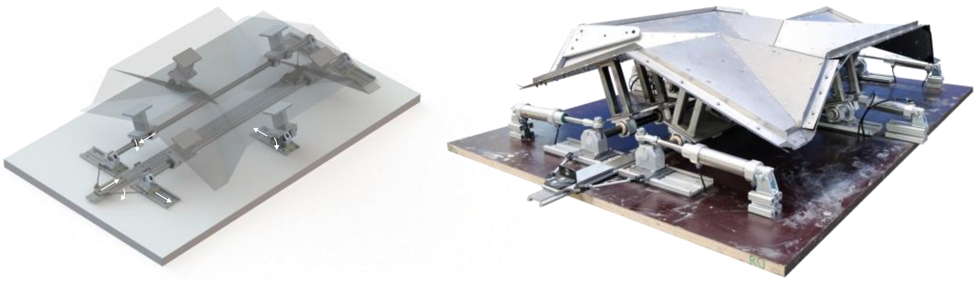

Figure 4.4. Kinematics and pneumatically actuated prototype of the folding tool in the folded state [38]

However, *Gomes et al.* [36] have shown that the prototype of the folding tool does not yet provide the manufacturing precision necessary to assemble large numbers of waterbomb modules. Current systematic geometric deviations in the manufactured modules largely result from inaccuracies in assembling the folding tool, specifically the drive and guiding components. The soft design of the joints on the tool's surface also plays a decisive role, as it does not represent an ideal revolute joint.

Future work will include developing a suitable joint design that exhibits higher stiffness and defined movements while providing sealing against concrete. This research relies on ongoing CT scans of a specially designed CT compatible joint test rig with a limited number of facets to analyze the interactions between concrete, reinforcement, joints, and the folding process. Furthermore, the gear mechanism in the tool's frame will be minimized so that, in the future, the facets will be primarily actuated directly by position-controlled pneumatic cylinders.

Especially when using stiff joints to allow for higher accuracy, pure position control of the tool surface with stiff actuators, e.g. electromechanical spindle drives, would require extensive path planning. If imperfect synchronization of the actuator movements during motion occurs or the tool surface requires small deviations from the calculated positions due to tolerances in manufacturing, significant internal stresses would result, which are associated with the risk of tool surface degradation or destruction. Here, the low stiffness of pneumatic actuators opens new possibilities, as despite position controlled, the tool surface is suspended by a set of soft actuators, allowing for simple overload protection thus limiting internal stress. Moreover, based on pneumatic elasticity, an incremental approach for position control can be pursued as described in the following.

For this incremental approach, three-dimensional geometry detection is required via a process-integrated optical measurement of the part geometry. A comparison of the current state with design data of the final component allows movement of the multiple actuators in small steps and thus an iterative stepping towards the final geometry. To fulfill the resulting requirements on actuator level, cylinder drives with small independent metering on/off valves and a pneumatic brake to allow for later hardening without crack inducing micro-motions are investigated.

This approach substantially reduces the number of sensors needed in the multi-actuator system in comparison to stroke sensor relying closed-loop position control of all actuators. Furthermore, switching valves reduce the risk for contamination induced downtime in comparison to servo-valves in the harsh environment. Hence, direct geometry control results in significant cost savings, higher robustness, and avoids extensive path planning and tolerance management on tool level. Additionally, geometric deviations in the tool surface resulting from manufacturing and joint design are directly accounted for.

The corresponding superordinate control system is still being developed that will transmit cylinder-specific step commands to the actuators by comparing the current geometry with the target geometry. Furthermore, current research is exploring additional possibilities for inline quality control, such as crack detection by means of the already installed optical system.

In future, the tool is intended to manufacture various geometries to ensure automated, economical production of user specific parts. To this end, the tool must achieve higher geometrical flexibility, as already identified by *Gomes et al.* [36]. Therefore, modifications to the tool surface and consequently to the actuators are necessary. Different concepts for the variation of the tool surface tessellation have been investigated. Replacing the entire tool surface with integrated joints while simultaneously reconfiguring the actuators has been identified as the most efficient approach. With this approach, a dedicated tool surface is available for each tessellation, while different geometries can be achieved per tool surface by altering the degree of folding.

Figure 4.5 shows a schematic illustration of the overall concept for the next generation of the folding tool. To adjust the drive system to varying target geometries, the pneumatic drives beneath the surface can be repositioned within the base frame according to the fold-specific requirements, and/or they can be substituted with actuators of varying lengths. Thus, the cylinders must be attached to the base frame and surface in a way that allows for easy relocation and exchange. For this, the base frame provides a large number of couplings for compressed air, which also serve as mechanical fixpoints between the cylinders and the tool frame, offering suitable mounting options. To facilitate use, the cylinders are equipped with decentralized electrical power supply, control, valves, and signal processing. These actuators, referred to as Servo-Pneumatic Actuators (SPA) in the following, can be implemented, for example, by integrating the pneumatic coupling, spherical joints, switching valves with a sufficiently low flow rate and a battery-powered microcontroller with wireless communication to a central control system, into a pneumatic cylinder with braking unit. The focus of the SPA is on positioning accuracy rather than achieving high travel speeds, as this is not necessary for the present application. The development of such SPA is the subject of current research at ifas.

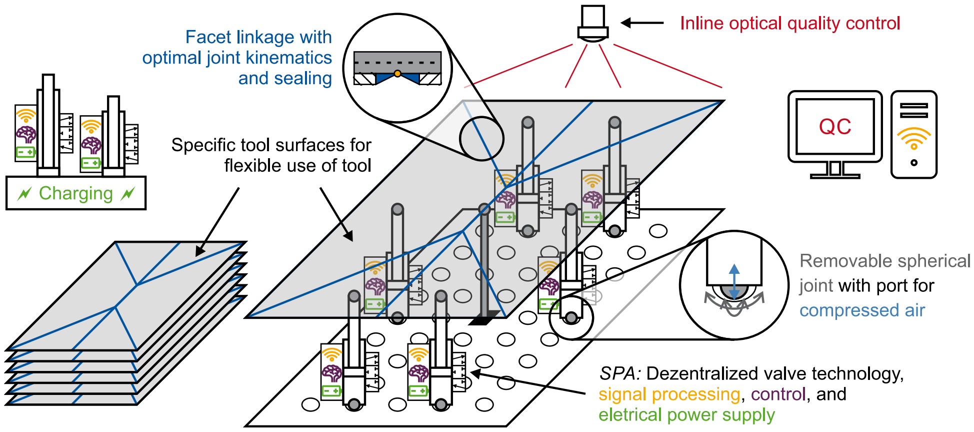

Figure 4.5. Overall concept for the next generation of the folding tool, featuring specific tool surfaces, Servo-Pneumatic Actuators, and inline optical quality control

5. Conclusion

The construction industry faces severe challenges to date and in near future. The global shortage in construction workers and requirements on low emissions will force battery electric mobile machinery with higher degrees of automation and new materials enabling novel construction principles with associated automated production methods into the market.

While the field of mobile construction machines is one of the leading markets for fluid power components and therefore in focus of many research initiatives, automated manufacturing of prefabricated concrete parts with significant potential for emission reductions is rarely investigated as a potential future market for fluid power. Especially, when it comes to high clamping forces, which are required for the formwork of heavy concrete parts, hydraulics is well suited to reach higher degrees of automation. Contrary to this, pneumatics can enable automation of specialized formworks and folding tools for lightweight and material efficient design and manufacturing methods. Additional research in this interdisciplinary field will be pursued at ifas.

6. Acknowledgement

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