Curtain Wall Installation for High-Rise Buildings: Critical Review of Current Automation Solutions and Opportunities

B. Johns[a], M. Arashpour[b] and E. Abdi[a]

[a]Department of Mechanical and Aerospace Engineering, Monash University, Australia
[b]Department of Civil Engineering, Monash University, Australia
E-mail: brandon.johns@monash.edu, mehrdad.arashpour@monash.edu, elahe.abdi@monash.edu

Abstract –

In the construction of high-rise buildings, the conventional methods for the on-site installation of prefabricated facade modules require considerable manual handling. This unsafe and inefficient practice can be solved through automation.

This paper critically reviews automated Unitized Curtain Wall (UCW) installation and discusses opportunities for future development, as found in adjacent fields. A generalized solution to the installation of UCW modules is applied to analyze the conventional method in safety, economic efficiency, and logistic viability.

Recent automation solutions control wall module vertical transport trajectories with guide rails or redundant parallel cables. Both approaches specialize in capability, leaving many installation scenarios unautomated. Opportunities for improvement exist in efforts to automate crane operations by development of robotic crane end effectors. Localization in uncertain conditions for automated feature detection can be improved by dynamically changing the operator interface. Directions to improve safety and efficiency of UCW on-site installation are identified and recommendations are presented.

Keywords –

Assembly; Automation; Construction; Control systems; Curtain wall; Facade; High-rise building; Installation; Robotics; Tower crane

1 Introduction

The method chosen to construct the exterior wall of a high-rise building can significantly affect the entire construction process [1, 2]. Consideration of worker safety, economic efficiency, and logistic viability is of high importance in choosing the optimal solution. Potential for construction delays is increased with reliance on shared workspace [1–3] and equipment [1, 2, 4].

The unitized curtain wall (UCW) is a non-structural facade that is potentially compatible with these considerations. UCWs are comprised of prefabricated modules, hence complex designs can be manufactured in low cost, high precision factory environments [5]. The on-site installation procedure is also faster compared to other wall types [5].

High-rise building facades commonly incorporate UCWs, but the conventional method for on-site installation is unsafe and inefficient [1]. During installation, curtain wall modules (CWMs) are lifted by crane, hoist, or telescopic handler to the attachment location and then fixed to brackets which are preinstalled on the building [6]. The conventional installation method requires considerable manual handling to guide the large, heavy, suspended wall modules into position [6]. This presents risk of collision which can cause human injury or damage to the CWM [3].

Automation of the on-site UCW installation procedure is a solution to these issues. However, the current automation solutions are limited in addressing only a small part of the installation procedure [7], or in scope of application [2, 8]. For example, many automation solutions are limited to handling only common types of CWM [2, 7, 8], hence they do not apply to custom designs as in [9].

Automation of high-rise construction, including curtain wall installation, was reviewed by Cai et al. [10, 11]. To increase interdisciplinary communication, it was suggested to review the advancement of basic technologies that can be utilized in high-rise construction [11]. Iturralde et al. explored the task of lifting CWMs from the ground to the attachment location for an optimal automation solution [12]. However, the scope of their research did not include informational tasks.

This paper critically reviews the state of the art in UCW installation methods and discusses the potential incorporation of related mechanical and informational technologies. A generalized solution to CWM vertical transportation from the ground to the installation point and precision alignment with the attachment location is presented. The relations among components of the solution are then discussed and flaws in the conventional installation methods are identified. Venues for further improvement are then determined through analysis of automation technologies in adjacent fields with respect to the generalized solution.

Section 2 describes the scope and methodology of this review. Section 3 then presents the generalized solution for vertical transport and precision alignment of CWMs, then discusses limitations in the conventional solution. In section 4, venues for improvement are suggested in the mechanical design as well as in the informational processes of sensing, analysis, operator feedback, and operator control. Conclusions and future research directions are then presented in section 5.

2 Research Scope and Methodology

The UCW installation procedure is described by Taghavi et al. [6] and Yu et al. [7]. The procedure comprises of designing the curtain wall, manufacturing CWMs, delivery to the construction site, vertical transportation to the installation point, alignment with the attachment location, and attachment of CWMs to the building. Within this procedure, the attachment interface on the building side can be prepared before, or at the point of, module attachment [6]. The scope of this paper is limited to the tasks of CWM vertical transportation and alignment with the attachment location. These tasks are particularly dangerous in the conventional procedure, while there is potential to significantly improve both safety and economic efficiency through mechanization and automation [1–4, 13].

This review includes literature directly related to UCW installation as well as literature from other fields where the mechanisms and processes are relevant to UCW installation. The reviewed mechanisms and processes are categorized in Figure 1.

The literature search mostly utilized the search engine 'Google Scholar' as a means to reduce bias towards specific research fields, conferences, or journals. Search keywords that were identified by Cai et al. [11] were utilized. The most relevant were 'curtain wall', or 'facade', with 'installation', 'assembly', 'automation', or 'robot'. Other keywords were identified through relating mechanisms and processes utilized during UCW installation. For example, 'crane' was combined with 'vision', 'mapping', 'localization', 'skew control', and 'operator assistance'. Results were filtered by title and then abstract, based on relevance. Further literature was found with the snowball methodology; by following the citations found in highly relevant literature.

Where large volumes of similar literature were found, only representative samples were selected to be discussed in this review. This increases the breadth of the review, as the review is intended to broadly survey the applicable technologies rather than focus on the individual implementation of each. The selection criteria weighed year of publication, number of citations, and relevance to UWC installation.

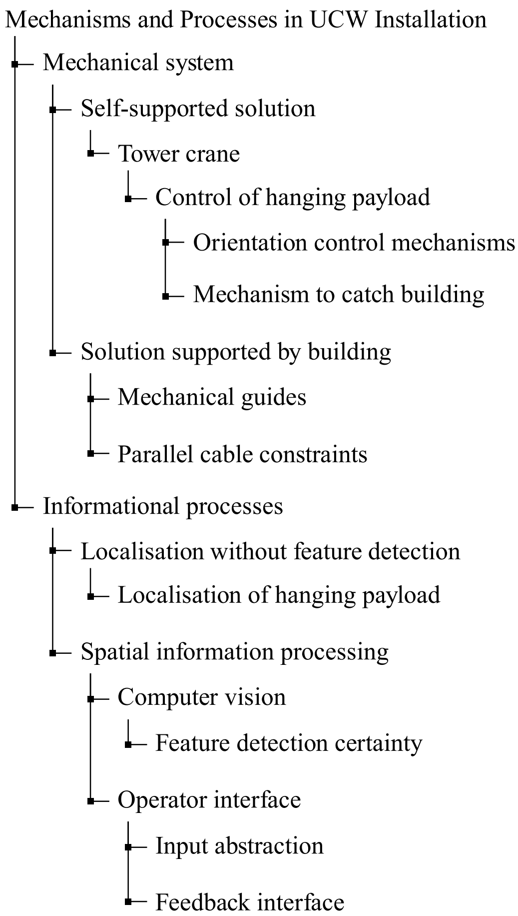

Figure 1. Reviewed mechanisms and processes

3 The UWC Installation Method

A generalized solution to CWM vertical transportation and precision alignment is presented in Figure 2. The desired state of the system has the CWM aligned to the attachment location. To achieve this, the decision-maker commands the hardware controller, which actuates the mechanical system toward the desired state. The state of the system is sensed, and the sensed information is pre-processed by the analysis unit before being fed back to the decision-maker. Information may also be sent directly from the sensors or analysis unit to the controller, creating an inner feedback loop to stabilize the system state by suppressing deviations from the command signal.

There are two main conventional UCW installation methods: direct and staged. Figure 3 presents the direct method. In this approach, CWMs are lifted directly from the ground to the attachment location with a crane or hoist. This method is used as a basis for comparison, rather than the staging methods described in [1, 3, 6, 7], as it is more similar to the most recent automation solutions [1, 2, 4, 6, 9]. The direct method is most appropriate for large and heavy CWMs. It is faster to install UCWs that are comprised of larger modules [2, 3, 14]. Additionally, by not requiring on-floor staging, the impact on other construction operations can be reduced [1, 2]. This follows the lean construction methodology of decoupling operations.

In the direct conventional method, the operator of the crane or hoist performs analysis and decision-making. Their role is to send commands to the hardware controller based on feedback from the sensors. The hardware controller actuates the mechanical system based on the operator's input. Feedback from crane pose measurement sensors allows tracking of the command and deployment of anti-sway technologies [15]. These sensors also feedback to the operator's user interface.

The crane 'dogman' is situated at the installation point. They perform sensing and analysis of spatial information for localization, and feedback this information to the operator [16]. In the case of a 'blind lift', where the crane operator cannot see the CWM directly, the operator is entirely dependent on the dogman. The dogman also performs decision-making and actuates the system to control the orientation and position of the CWM during the alignment phase. With their interdependent responsibilities, the crane operator and dogman must operate in unison. Hence the installation speed is limited by the speed of communication between the crane operator and dogman [17].

This indicates that the safety and efficiency of UCW installation can be improved through automation of the work conventionally performed by the dogman. The effectiveness of removing the dogman is supported by the results of research to automate crane operations, as applied in adjacent fields. Crane operator performance can be improved in safety and efficiency through utilization of automated systems to sense, analyze and feedback spatial information [13]. Mechanization of payload orientation control with an active rotary crane hook is economically beneficial and greatly increases safety [18]. Combining an active rotary crane hook with automated alignment sensing and analysis unit can increase the speed of alignment operations [19].

The solution to safe and efficient CWM vertical transportation and precision alignment requires unison in communication between the systems that perform decision-making, control, actuation, sensing, and analysis. The utilization of a dogman impedes effective communication. The minimum requirements to remove the dogman are automation of sensing and analysis, and mechanization of precision positioning.

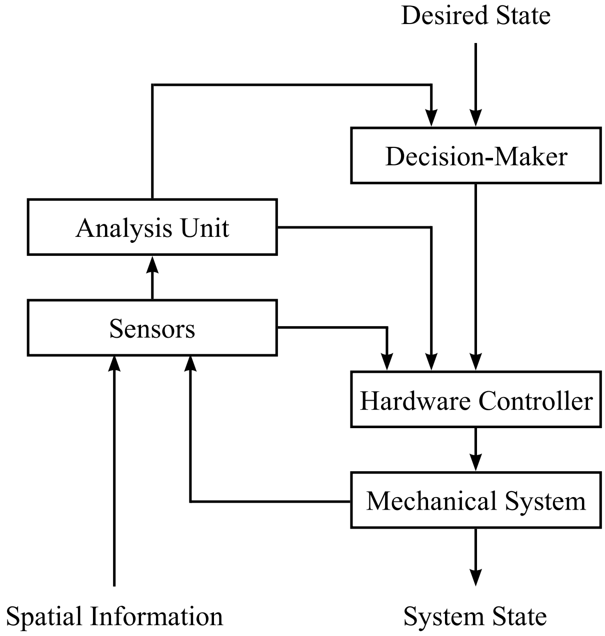

Figure 2. Generalized solution to UCW assembly

Figure 3. Direct conventional UCW installation method: Transitioning from the vertical transport task to the alignment task (photo by B. Johns, 2019)

4 Discussion of Technologies Relevant to UCW Installation

This section explores opportunities for improvement in each UCW installation mechanism and process, with the objective to eliminate the requirement of a dogman in CWM vertical transportation and precision alignment. It is assumed that an operator will be required, hence fully autonomous path planning and logistics is not explored.

4.1 Mechanical System

Mechanical requirements of the solution are CWM loadbearing, vertical transport to the attachment location, and precise position and orientation control with 1mm tolerance [8, 20].

To better interface CWMs with robotic tools, many automation solutions require specific or custom UCW designs [1, 2, 12]. This also simplifies the automation of processes that vary significantly with variation in curtain wall design, such as the automated fixing of an aligned CWM to the building. However, limiting the application of the solution to compatible designs of curtain wall could cause long term problems. For example, the solution by Friblick et al. [1] does not allow for CWMs to be installed with any procedure other than the intended procedure. Hence, repairs to and disassembly of the proprietary mechanism may require special parts and tools that have ceased being produced during the lifespan of the UCW. Thus, we mainly highlight solutions that are compatible with existing designs of curtain wall.

The most appropriate class of robot for performing high-rise UCW installation without on-floor staging, has previously been assessed as the hanging robot [12]. A challenge for hanging systems is to control all degrees of freedom (DOF) with the precision required for the alignment operation. In the conventional solution, a single vertical hoist cable usually supports the CWM. This system is highly underactuated and susceptible to wind induced oscillations [21], hence the need for a dogman to perform fine position and orientation control.

Two approaches to control a hanging system are to either suppress oscillations with control systems or to introduce additional kinematic constraints. Given the large workspace, the only practical available stationary reference for constraint is the building that is under construction [12]. For example, an effective strategy is to attach guide rails to the building and hoist CWMs along the single remaining DOF [1, 2]. In constrained systems, it is often required for the building to support the load of the installation system and CWM. This increases potential to significant cost reduction [1–3]. Conversely, this may not be practical if the geometry of the building is not suitable or if higher floors are not yet completed. The following discussion is divided into solutions that require the load of the CWM to be supported by the building, and solutions that can independently support the load.

4.1.1 Self-Supported Solutions

Tower cranes are, to the best of our knowledge, the only independent load support structure deployed in high-rise UCW installation. The lack of utilization of other types of support body in high-rise construction indicates that no other independent support structure is practical, backed by the analysis by Iturralde et al. [12]. In the crane supported installation method, any geometry of CWM can be lifted to any attachment location that is not below overhanging building geometry. Hence, this method can be deployed to almost any application. The requirement of situating a tower crane on-site is typically satisfied due to the requirements of other on-site construction operations, and the crane can be shared amongst these operations [1].

To achieve the positional accuracy required for UCW installation, all vibrational modes of the suspended CWM should be suppressed. For a load supported by a single vertical cable, such as a crane suspended load, while allowing for elasticity of the cable, there are 6 DOF of vibrational modes. They are sway (pendulum swinging of the hook with 2 DOF), roll (payload tilting about the hook with 2 DOF), skew (rotation about the cable axis with 1 DOF), and heave (linear oscillation along the cable axis with 1 DOF) [22]. Based on a 2017 review of crane control systems [21], most research considers only the sway modes with a few considering the roll modes. Very little research considers skew [23] or heave [21].

Heave, roll, and sway oscillations can be controlled with regular tower crane motions; however, control is underactuated. Furthermore, the rotational motion of the jib about the tower (slewing), has highly coupled non-linear dynamics, making control of the payload very difficult [21]. Hence, to achieve the positional accuracy needed to install a CWM, an additional mechanism is required.

With the assumption that the alignment roll orientation is consistent for each application and does not need to be changed often, the roll orientation can be manually set to the aligned orientation before the lift operation by adjusting the rigging configuration. In this case, pre-setting the roll orientation and passively or actively suppressing roll oscillations does not limit the system capabilities. If this assumption is not valid, then a mechanism that translates the center of mass relative to the hook can adjust roll orientation by small angles [24].

Active skew control is necessary to perform alignment with complex building geometry or when using slewing cranes [25]. Several devices have been developed which utilize heavy flywheels to exert skew torque through conservation of angular momentum [19, 26]. These devices can become saturated and must be heavy to be effective. Another method of skew control is seen on harbor cranes. For slewing harbor cranes, skew control is achieved with an active rotary crane hook (also known as a 'Rotator' or 'Power Swivel') [23, 25, 27, 28]. For system stability, at least two separated cables must connect the trolley and hook block. Full scale outdoor experiments show that very small skew error is achievable [25], likely to a degree that is sufficient for UWC installation.

To aid in vibration suppression when the CWM is near to the building, the building and the previously installed CWMs can act as reactionaries. A manipulator can take hold of the building and drive the CWM into position by utilizing the sway degrees of freedom [29] or an extendable hook attachment [30]. For the gripper type, inspiration can be taken from harbor crane operations, where the spreader is mechanically aligned to the target container with 'flippers'. The flippers are driven closed onto the edges of the container from all directions, mechanically forcing the parts into alignment.

For the swaying manipulator to catch the reactionary, an impulsive load will be generated. Thus, to prevent damage to the building or CWM, dampening of the collision is required. This problem has been investigated in research to assemble suspended large steel beams, where a pre-acting control strategy has been proposed [29]. An adaptation would need to be made for the swaying crane end-effector to catch the building instead of the other way around.

4.1.2 Load Supported by the Building

Rather than lifting CWMs to the attachment location and then catching the building for stability, CWMs can be guided through a constrained path throughout the entire lift. As risk of damage by collision with the building is eliminated, the lift path can stay close to the building for the entire lift [1–3]. This allows for performing the lift with a hoist that is mounted on the building, thus eliminating dependence on the expensive tower crane. The building can also support any constraining fixtures.

Kinematic constraints in current UCW installation methods include guide cables [3] or guide rails [1, 2]. These constraints limit application to geometrically prismatic buildings that can support the mass of the hoist and CWM from the location of the hoist. Furthermore, the guide rails themselves must be installed without the aid of guide rails, requiring dangerous manual labor. An alternative approach is to constrain the orientation with tensioned cables, terminated at, and attaching each corner of the CWM to the ground [31]. However, guide cables may not be feasible for automated alignment due to interference with the already installed CWMs.

In another approach, a redundantly cable-driven parallel robot for UCW installation is currently in development [6]. Tensioned cables connect the robot to the corners of the building face, over-constraining the floating robot. Even with this design, to achieve 1mm precision with the end effector, a secondary robot arm is attached to the cable suspended base through a passive damper [8, 32]. Hence this robot has many DOF, which is not ideal for cost or maintenance. Another limitation of the design is that for flat faced buildings, the constraint cables will be closely in-plane, which leaves the design sensitive to out-of-plane disturbances [33]. Additionally, the cable tension must increase as the angle of the cable from vertical increases [33]. Very large cable tension would then be required to install the top row of CWMs which the building may not be designed to withstand.

The main challenges for the mechanical system to vertically transport and precisely align CWMs are to achieve high positional accuracy and suppress vibration. Supporting the load of the system with the building has many advantages but is not suitable for every application. Supporting the CWM with a tower crane can be deployed to almost any application, but vibration suppression is more difficult. A specialized crane end effector is a potential solution to this problem.

4.2 Informational Processes

The hardware controller requires feedback of the system state to perform command tracking, and the decision-maker requires feedback of spatial information to perform path planning (Figure 2). The state of a crane system is typically characterized with pose and load measurements [27, 34], while the spatial information to feedback is dependent on the required input.

4.2.1 Localization Without Feature Detection

Measurement of the system state is a requirement of setpoint command tracking and oscillation suppression. The positional tolerance requirement of the alignment task is 1mm [8, 20]. Hence the position of the CWM relative to the attachment location needs to be measured to this tolerance. If a map of the workspace is acquired, then accurate measurement of the pose of the system is sufficient for localization.

The state of the art techniques in crane pose measurement to estimate the payload location are insufficient in accuracy and reliability for application to CWM alignment [34]. However, the nature of UCW installation separately requires both large payload displacement and accurate positioning. Hence it may be practical to utilize separate measurement systems for each task. Pose measurement can be utilized during vertical transport, as well as to deploy anti-sway technologies.

A challenge in pose measurement is determining the location of the hanging payload. The sway angle of the cable can be measured by aiming a camera horizontally at the top segment of the cable [35]. Robustness to changes in background light levels can be achieved by utilizing an infrared camera and emitter [36]. Sway and skew can be measured together by fusing the data from an inertial measurement unit (IMU) placed on the hook block, with feed from a camera pointing down from the top of the hoist [34]. However, the reliability of computer vision techniques to identify the payload with a downward pointing camera is subject to lighting conditions, hoist length, and similarity between the colors in the background to the payload.

4.2.2 Measurement, Analysis, and Feedback of Spatial Information

Measurement of spatial information can supplement the low accuracy of crane pose measurement. CWM alignment can be measured relative to a fiducial feature of the target, by utilizing a camera or laser scanner mounted on the crane hook block. For example, a camera mounted on a crane spreader can reliability detect and locate the lock holes of shipping containers [37]. Relative alignment to adjacent CWMs can be measured accurately with computer vision utilizing structured lasers by analyzing the gaps between CWMs [38]. Error accumulation from relative measurements can be corrected by aligning measurements taken at a known location to a CAD model of the building [9].

In case of low certainty in feature detection, the operator can assist in analysis. For example, the operator can select the locations of bolt holes from a camera feed to provide a region of convergence to the feature detection algorithm [39]. After the alignment target has been identified, the controller can then perform path planning and complete the alignment semi-autonomously. This requires abstracting the operator input into higher level actions and programming the controller to decompose the task into actuator inputs [40]. This separates their decision from the action generated by internal feedback. This separation is beneficial, as absence of separation creates conflict between the operator and internal feedback anti-sway systems [15].

Another source of conflict in the operator interface is feedback. Depending on the operators perception of a tasks difficulty, feedback may be interpreted as either helpful or distracting [13]. To keep feedback relevant to the current task, it may be appropriate to use separate interfaces for large payload displacement and accurate positioning. Since these tasks are completed separately, the interfaces will not interfere with each other.

Only the required feedback should be provided to the operator [13]. Providing too much feedback increases the operator's mental workload in performing analysis, which increases their reaction time. Pre-processing and analysis of camera feed to draw attention to the relevant information is common solution in research. A map can be generated by piecing together images captured by an overhead camera at different crane orientations [41]. The height of obstacles can be highlighted by thresholding rangefinder data [42]. However, trials of an operator feedback system indicated that a raw camera view should still be provided [43], which may increase operator trust in the system and also provide a fallback in case of poor operating conditions for automated analysis.

Lee et al. fused sensor data with the CAD model of the construction site [43]. The simulated camera views were feed back to the operators display. It was concluded that split 2D top and side views are easier to interpret than a 3D view. Additionally, the interface for altering the feedback display should be simple and preferably hands free. In a similar approach, Chen et al. pre-processed sensor data with a game engine to create a 3D workspace visualization [34]. This is presented to the operator through a similar interface which is manipulated with voice control.

The main challenges in automating the informational processes required for UCW installation are precise localization of CWMs and managing the information feedback to the operator. Sensing of the system pose is inadequate in accuracy for alignment, but relative localization with computer vision is viable. Dynamically changing the control and feedback interface is a potential solution to keep the user interface relevant to the current task.

5 Conclusions

The UCW installation automation solutions currently deployed and under development are limited in scope of application. Limitations include requirement for the building to support the transport mechanism, requirement of custom designs of curtain wall, incompatibility with complex building geometries and existing designs of curtain wall, and solution complexity.

Research to automate large steel beam assembly provides potential solutions to better constrain a CWM. Compared to construction operations, a high level of precision and automation is achieved in harbor crane operations to move shipping containers. The requirement of a dogman is removed by introducing an active rotary crane hook, and high positional accuracy is achievable through control systems.

Measurement of the pose of a crane to estimate the payload location is insufficiently accurate for CWM alignment. Computer vision can be used instead. Operator input can be combined with automated analysis to improve feature detection. The operator is a feedback controller, and hence their interface is an essential part of the system. Removing the lag caused by the slow communication between the dogman and the operator can improve both safety and installation speed. Pre-processing of feedback and careful choice of the relevant information to feedback is required.

Further research is recommended to develop an automated UCW installation solution that is widely applicable to different types of curtain wall, building geometry, and building load capacity; addressing situations where the more specialized solutions do not apply, for example, in refurbishing projects or when installing unusually shaped CWMs. The solution should primarily aim to mechanize and automate the tasks that are conventionally completed by the dogman. This will result in a safer and more economically efficient installation methodology.

Acknowledgements

This research was supported by an Australian Government Research Training Program (RTP) Scholarship.

References

[1] Friblick F., Tommelein I. D., Mueller E., and Falk J. H. Development of an Integrated Facade System to Improve the High-Rise Building Process. In *17th Annual Conference of the International Group for Lean Construction*, pages 359–370, 2009.

[2] Falk H., Andersson H., Friblick F., and Mul M. J. A Novel Facade System to Improve the Whole High-Rise Building Process. In *CTBUH 2016*, pages 1077–1086, 2016.

[3] Tommelein I. D. and Beeche G. De-Coupling Cladding Installation From Other High-Rise Building Trades: A Case Study. In *Proceedings of the 9th Annual Conference International Group for Lean Construction, Singapore*, 2001.

[4] Pan W., Bock T., Linner T., and Iturralde K. Development of a fast and effective solution for on-site building envelope installation. In *Proceedings of the 33rd International Symposium on Automation and Robotics in Construction (ISARC2016)*, 2016.

[5] Vigener N. P. and Brown M. A. Building Envelope Design Guide - Curtain Walls. National Institute of Building Sciences, 2016.

[6] Taghavi M., Iturralde K., and Bock T. Cable-driven parallel robot for curtain wall modules automatic installation. In *Proceedings of the 35th International Symposium on Automation and Robotics in Construction (ISARC2018)*, pages 396–403, 2018.

[7] Yu S. N., Lee S. Y., Han C. S., Lee K. Y., and Lee S. H. Development of the curtain wall installation robot: Performance and efficiency tests at a construction site. *Autonomous Robots*, 22(3):281–291, 2007.

[8] Taghavi M., Kinoshita T., and Bock T. Design, Modelling and Simulation of Novel Hexapod-Shaped Passive Damping System for Coupling Cable Robot and End Effector in Curtain Wall Module Installation Application. In *Proceedings of the 36th International Symposium on Automation and Robotics in Construction (ISARC)*, pages 665–671, volume 36, 2019.

[9] Liang Y., Che Z., Chen X., and Liu C. Total Assembly Construction Technology of Ultra-long Variable Cross-section Spiral Aluminum Plate Unit of Qingdao Citizen Fitness Center Sports Stadium. *Engineering and Applied Sciences*, 4(5):98, 2019.

[10] Cai S., Ma Z., Skibniewski M., Guo J., and Yun L. Application of automation and robotics technology in high-rise building construction: an overview. In *Proceedings of the 35th International Symposium on Automation and Robotics in Construction (ISARC2018)*, pages 1–8, 2018.

[11] Cai S., Ma Z., Skibniewski M. J., and Bao S. Construction automation and robotics for high-rise buildings over the past decades: A comprehensive review. *Advanced Engineering Informatics*, 42:100989, 2019.

[12] Iturralde K., Linner T., and Bock T. Comparison of Automated and Robotic Support Bodies for Building Facade Upgrading. In *Proceedings of the 32nd International Symposium on Automation and Robotics in Construction and Mining (ISARC2015)*, 2015.

[13] Fang Y., Cho Y. K., Durso F., and Seo J. Assessment of operator's situation awareness for smart operation of mobile cranes. *Automation in Construction*, 85:65–75, 2018.

[14] Iturralde K., Linner T., and Bock T. Development and preliminary Evaluation of a concept for a Modular End-Effector for automated/robotic Facade Panel Installation in Building Renovation. In *Proceedings of the 10th Conference on Advanced Building Skins*, 2015.

[15] Vaughan J., Karajgikar A., and Singhose W. A study of crane operator performance comparing PD-control and input shaping. In *Proceedings of the 2011 American Control Conference*, pages 545–550, 2011.

[16] Workplace Health and Safety Queensland. A Guide for doggers. 2010.

[17] Shapira A., Rosenfeld Y., and Mizrahi I. Vision System for Tower Cranes. *Journal of Construction Engineering and Management*, 134(5):320–332, 2008.

[18] Lee C. and Lee G. Feasibility of beam erection with a motorized hook-block. *Automation in Construction*, 41:25–32, 2014.

[19] Liang C.-J., Kang S.-C., and Lee M.-H. RAS: a

robotic assembly system for steel structure erection and assembly. *International Journal of Intelligent Robotics and Applications*, 1(4):459–476, 2017.

[20] Han C. S., Lee S. Y., Lee K. Y., and Park B. S. A multidegree-of-freedom manipulator for curtain-wall installation. *Journal of Field Robotics*, 23(5):347–360, 2006.

[21] Ramli L., Mohamed Z., Abdullahi A. M., Jaafar H. I., and Lazim I. M. Control strategies for crane systems: A comprehensive review. *Mechanical Systems and Signal Processing*, 95:1–23, 2017.

[22] Arena A., Casalotti A., Lacarbonara W., and Cartmell M. P. Dynamics of container cranes: three-dimensional modeling, full-scale experiments, and identification. *International Journal of Mechanical Sciences*, 93:8–21, 2015.

[23] Ho T., Suzuki K., Tsume M., Tasaki R., Miyoshi T., and Terashima K. A switched optimal control approach to reduce transferring time, energy consumption, and residual vibration of payload's skew rotation in crane systems. *Control Engineering Practice*, 84:247–260, 2019.

[24] Wehrli R. F. and Gallione J. Method and Apparatus for Vertically Orienting Precast Concrete Wall Panels. U.S. Patent WO2011028879A12011.

[25] Schaper U., Dittrich C., Arnold E., Schneider K., and Sawodny O. 2-DOF skew control of boom cranes including state estimation and reference trajectory generation. *Control Engineering Practice*, 33:63–75, 2014.

[26] Inoue F., Wiuanabe K., Ikeda Y., Wakisaka T., Wakabayashi A., and Nekomoto Y. A Practical Development of the Suspender Device that Controls Load Rotation by Gyroscopic Moments. In *Proceedings of the 14th International Symposium on Automation and Robotics in Construction (ISARC)*, pages 486–495, 1997.

[27] Liebherr. Liebherr Port Cranes FCC and TCC. 2011.

[28] Cibicik A., Myhre T. A., and Egeland O. Modeling and Control of a Bifilar Crane Payload. In *2018 Annual American Control Conference (ACC)*, pages 1305–1312, 2018.

[29] Kyungmo J., Dongnam K., Kihyun B., Daehie H., Shinsuk P., and Myo-Taeg L. Pre-acting manipulator for shock isolation in steel construction. In *2007 International Conference on Control, Automation and Systems*, pages 1203–1208, 2007.

[30] Hatton I. G. M. Fly jib for a crane and method of use. U.S. Patent US8979148B12015.

[31] Seung-Kyou L., Nakju Lett D., Gwi-Tae P., Kyung-In K., Myo-Taek L., Dae-Hie H., Shin-Suk P., Ung-Kyun L., and Tae-Koo K. Robotic technologies for the automatic assemble of massive beams in high-rise building. In *2007 International Conference on Control, Automation and Systems*, pages 1209–1212, 2007.

[32] Taghavi M., Heredia H., Iturralde K., Halvorsen H., and Bock T. Development of a Modular End Effector for the installation of Curtain Walls with cable-robots. *Journal of Facade Design and Engineering*, 6(2):1–8, 2018.

[33] Jung K., Chu B., and Hong D. Robot-based construction automation: An application to steel beam assembly (Part II). *Automation in Construction*, 32:62–79, 2013.

[34] Fang Y., Chen J., Cho Y. K., Kim K., Zhang S., and Perez E. Vision-based load sway monitoring to improve crane safety in blind lifts. *Journal of Structural Integrity and Maintenance*, 3(4):233–242, 2018.

[35] Smoczek J., Szpytko J., and Hyla P. The anti-sway crane control system with using dynamic vision system. In *Solid State Phenomena*, pages 589–593, volume 198, 2013.

[36] Hyla P. Night vision applicability in anti-sway vision-based solutions. In *2015 20th International Conference on Methods and Models in Automation and Robotics (MMAR)*, pages 358–363, 2015.

[37] Diao Y., Cheng W., Du R., Wang Y., and Zhang J. Vision-based detection of container lock holes using a modified local sliding window method. *EURASIP Journal on Image and Video Processing*, 2019(1):69, 2019.

[38] Li H., Duan X., Zhan Y., and Gao L. A Handle Inspection Device for Curtain Wall Installation based on Structured Laser. In *2016 IEEE International Conference on Mechatronics and Automation*, pages 1623–1628, 2016.

[39] Chu B., Jung K., Lim M.-T., and Hong D. Robot-based construction automation: An application to steel beam assembly (Part I). *Automation in Construction*, 32:46–61, 2013.

[40] Lytle A. M. and Saidi K. S. NIST research in autonomous construction. *Autonomous Robots*, 22(3):211–221, 2007.

[41] Wang Y., Suzuki H., Ohtake Y., Kosaka T., and Noguchi S. Generating a visual map of the crane workspace using top-view cameras for assisting operation. In *Proceedings of the Creative Construction Conference (CCC2018)*, 2018.

[42] Domingue B. and Vaughan J. Crane Workspace Mapping via a Scanning Laser Rangefinder. In *ASME 2015 International Mechanical Engineering Congress and Exposition*, volume 4A, 2015.

[43] Lee G., Cho J., Ham S., Lee T., Lee G., Yun S.-H., and Yang H.-J. A BIM- and sensor-based tower crane navigation system for blind lifts. *Automation in Construction*, 26:1–10, 2012.