Data driven simulation models

Recent studies have addressed the longstanding challenge of generating adaptive simulation models that are responsive to the project dynamic changes during the construction stage. Recent efforts took advantage of tracking technologies to capture trucks and [excavator](https://www-sciencedirect-com.mtu.idm.oclc.org/topics/engineering/excavators) motions and enhance the detection of equipment state [[34]](https://www-sciencedirect-com.mtu.idm.oclc.org/science/article/pii/S0926580516300930#bb0170), [[35]](https://www-sciencedirect-com.mtu.idm.oclc.org/science/article/pii/S0926580516300930#bb0175). Song and Eldin [[44]](https://www-sciencedirect-com.mtu.idm.oclc.org/science/article/pii/S0926580516300930#bb0220) highlighted the ineffectiveness of using statistical input data for simulation models to analyze look-ahead schedules, which, for precision, require the most recent project performance data on a real-time or near-real-time basis. The authors proposed an adaptive real-time tracking and simulation of heavy construction operations using sensors to constantly capture and feed the dynamic site condition changes into the simulation for more accurate look-ahead scheduling. Akhavian and Behzadan [[45]](https://www-sciencedirect-com.mtu.idm.oclc.org/science/article/pii/S0926580516300930#bb0225), [[46]](https://www-sciencedirect-com.mtu.idm.oclc.org/science/article/pii/S0926580516300930#bb0230) employed data mining methods to extract contextual knowledge from heterogeneous field data that are captured through ubiquitous sensors to automatically generate and refine a simulation model. Further, the authors used built-in smartphone sensors to detect data other than positional information to recognize construction equipment activities [[47]](https://www-sciencedirect-com.mtu.idm.oclc.org/science/article/pii/S0926580516300930#bb0235). Although, all such studies provided means of realistic input data for simulation models, their utilization for simulation driven visualization is limited with one-way data flow; hindering the full benefit of real-time visualization models.

(ElNimr et al., 2016)

ElNimr, A., Fagiar, M. and Mohamed, Y. (2016) ‘Two-way integration of 3D visualization and discrete event simulation for Modeling Mobile Crane movement under Dynamically Changing Site Layout’, *Automation in Construction*, 68, pp. 235–248. doi:10.1016/j.autcon.2016.05.013. Available at: https://library.ittralee.ie/ (Accessed 23 November 2023).

5.2. Suspension model

This section introduces the principle of constraint-based rigid body dynamics and describes how to formulate the motions of the suspension model using this principle. It is mainly used for simulating the physical motions of articulated objects. The articulated objects can be treated as systems with specific types of constraints among connected joints and contact planes. These constraints represent the limitations of motion and place restrictions that cause the virtual objects to act as they would in the real physical world. For example, the constraints can be formed as the movement range of joints, contact points which exhibit spring-like or stiff reactions, and even the behaviors of motors.

In this research, the joint descriptions of the suspension model are identified. We use the methodology of formulating the constraints, followed by applying constraint-based rigid body dynamics. The basic idea for formulating all kinds of constraints is to represent them in a matrix form. First, we take the ball-in-socket joint as an example. The detailed formulating procedures can be referenced from previous works [[15]](https://www-sciencedirect-com.mtu.idm.oclc.org/science/article/pii/S0926580510000488#bib15) and other references [[16]](https://www-sciencedirect-com.mtu.idm.oclc.org/science/article/pii/S0926580510000488#bib16), [[17]](https://www-sciencedirect-com.mtu.idm.oclc.org/science/article/pii/S0926580510000488#bib17). Second, we explain how the model of the suspension part of the crane is constructed.

The number of degrees of freedom (DOFs), which is the minimum set of parameters needed to describe the motion of a rigid object in the system, is the key part of the constraints formulation. A free moving body has six DOFs: three parameters, *x*, *y*, and *z*, to describe its position and three parameters, ω, ψ, and κ to describe its orientation. If there are two bodies *Bi* and *Bj* in the system, we have twelve DOFs. The general form *P* for describing these two bodies can be represented as follows:



A fixed connection between two rigid bodies *Bi* and *Bj* reduces the number of DOFs of the system to six. Similarly, if rigid bodies *Bi* and *Bj* are connected together by another kind of joint, some of the DOFs can be removed, the number depending on the type of connection. However, the maximum number of DOFs that can be removed is six.

Assume that the *l*'th joint is a ball-in-socket joint between the two bodies *Bi* and *Bj* as represented in [Fig. 4](https://www-sciencedirect-com.mtu.idm.oclc.org/science/article/pii/S0926580510000488#fig4). With equality in the *x*, *y*, and *z* dimensions at the common point we can formulate three equations as follows:

A math equations on a white background

Description automatically generated

*Pi* and *Pj* are the position vectors of *Bi* and *Bj* respectively, *Ri* and *Rj* are the corresponding rotation matrices of each body's orientation, and *Pi*anc and *Pj*anc are the anchor vectors which represent each body's center of mass to the connected point. By formulating these three constraint equations, three DOFs can be removed from the joint.

A diagram of a joint

Description automatically generated

Fig. 4. Constraint formulation for a ball-in-socket joint.

If we reorganize these formulations, the constraint equations can be represented by the following vector form:

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By using the same rules for other types of joints, we can find the same expression Φ(*P*) but with a different row *m*, which represents the number of constraints or removed DOFs. The removed DOFs imply restrictions on the movement capability of the joint.

Now we explain how the suspension model of the crane is constructed. We built the suspension model of the crane by imitating the relationship of connections between each piece. The cable and hook on the suspension model present dynamic motions and are easily influenced by wind force, suspended objects, and so on. To simulate the natural properties of these components, we use ball-in-socket joints and slider joints to represent the DOFs potentially required on the model. [Fig. 5](https://www-sciencedirect-com.mtu.idm.oclc.org/science/article/pii/S0926580510000488#fig5) illustrates the configuration of joints on the suspension model. The ball-in-socket joints attached between the hook and the cable or the cable and the top of boom represent the relative movements during a swinging situation. Following the same idea, we divide the cable into several pieces and consider the ball-in-socket joints as connectors within each part. For extension and shortening movements, we also attach slider joints on the cable. Thus, the flexibility of the cable can be simulated to provide physical suspended actions during an erection simulation.

A diagram of a swing and a hook

Description automatically generated

Fig. 5. The connection relationships of the suspension model: (a) illustration and joints configuration in static condition; (b) illustration and joints configuration in swinging condition.

(Chi & Kang, 2010)

Chi, H.-L. and Kang, S.-C. (2010) ‘A physics-based simulation approach for cooperative erection activities’, *Automation in Construction*, 19(6), pp. 750–761. doi:10.1016/j.autcon.2010.03.004. Available at: https://library.ittralee.ie/ (Accessed 23 November 2023).

(Hung & Kang, 2013)

Hung, W.-H. and Kang, S.-C. (2013) ‘Configurable model for real-time Crane Erection Visualization’, *Advances in Engineering Software*, 65, pp. 1–11. doi:10.1016/j.advengsoft.2013.04.013. Available at: https://library.ittralee.ie/ (Accessed 23 November 2023).

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AMQP - Advanced Message Queuing Protocol

API – Application Programming Interface

AR – Augmented Reality

BDA – Big Data Analytics

BIM – Building Information Modelling

CAD – Computer-Aided Design

CM – Cloud Manufacturing

CoAP - Constrained Application Protocol

CPS – Cyber-Physical Systems

DIAMND – Diagnostics and Monitoring

ERP – Enterprise Resource Planning

FTP – File Transfer Protocol

HTTP – Hypertext Transfer Protocol

IMAP - Internet Message Access Protocol

IoT – Internet of Things

OLE - Object Linking and Embedding

OPC-UA – OLE for Process Control Unified Architecture

PLC – Programmable Logic Controller

PLM – Product Lifecycle Management

POP3 - Post Office Protocol

RFID – Radio Frequency Identification

SMTP - Simple Mail Transfer Protocol

SQL – Structured Query Language

TCP/IP - Transmission Control Protocol/Internet Protocol

UDP - User Datagram Protocol

VR – Virtual Reality

XMPP - Extensible Messaging and Presence Protocol