

# Using 3D direct manipulation for real-time structural design exploration

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## ABSTRACT

Impact of decisions in the design process is initially high and declines as the design matures. However, few computational tools are available for the early design phase, thus an opportunity exists to create such tools. New technology opens up new possibilities to create new and novel computational tools. In this work an existing application is adapted for a new novel 3D input device that is named the Leap Motion controller. The controller allows the user to interact with 3D objects on the screen by using fingers and hands. The of result of this work is a conceptual design application which enables very direct manipulation of 3D objects on the screen, which has not before been achieved for this type of application in 3D. An improved human-computer interaction can potentially improve the users understanding of the structural behavior of a model, cognitive engagement in the design task, and encourage further design exploration. Three different cases are implemented which aims to enable the user to explore different design options with emphasis on geometrical form, as this has the greatest potential to improve the structural performance. The case studies demonstrate new potential for building engineering intuition and improving design space exploration through very direct manipulation in 3D.

## KEYWORDS

Interactive structural analysis; Interactive structural form finding; 3D input device; Dynamic relaxation; Conceptual structural design

## 1. Introduction

The object of this paper is to demonstrate how an interactive 3D environment can improve conceptual structural design. The goal is to improve the users understanding of the structural behavior of a model and to illustrate how geometrical modifications changes the structural performance of the model.

### 1.1. Conceptual design tools

The earliest phase of the design process is referred to as the conceptual design phase. Decisions made in this phase have the highest impact of decisions made throughout the design process [38], the impact of decisions then declines as the design matures. The importance of the conceptual design phase is often overlooked and structural aspects are often only considered in a late design stage [33]. A contributing factor to this is that very few computational tools are available for conceptual design. The challenge with developing such computational tools is the fuzzy nature of the problem, knowledge and constraints of the problem are imprecise and incomplete [11]. Conventional advanced structural analysis software requires precise knowledge of the problem and are insufficiently agile to follow a designer's iterative workflow. It has been shown that premature use of such

software can negatively affect the quality of the conceptual design [9]. Conventional structural analysis software is developed for use in the late design stage, when the major design decisions have been made, as a tool for the engineer to verify the form.

Many different geometric modeling tools are today available for architects. These geometric modeling tools have since the introduction in the 1980 s grown increasingly sophisticated, and have together with the widespread perception of the benefits of technological innovation created a more intimate relationship between technology and design. This relationship has resulted in parametric design and scripting methods that can generate complex shapes and forms [31]. The distinct separation that architects use geometric modeling tools and engineers use analysis tools further reinforces the architects role as form-giver and the engineer as form-verifier [23]. To move away from this separation, the term 'designer' will be used in this paper to represent either an engineer or an architect.

The type of design tool that is used to generate and represent ideas also affects the quality and quantity of early prototypes. It was shown in [12] that physical prototyping generated a higher quantity of prototypes under a limited amount of time. The developed prototypes were also perceived as more novel compared to the prototypes that

where developed using CAD or conventional sketches. However, the prototypes that were perceived as more novel tended to fare poorly on all other measureable qualities [12]. As conceptual design is important and few conceptual design tools are available, an opportunity exists to improve the design process by developing such tools.

With new technology such as novel input devices and increased computational power comes new possibilities. The present work make use of these possibilities to create a new novel way to interact with, and create, digital prototypes. Where the prototypes in this work are structural models. As a computational model is used measureable performance can be computed and presented in real-time for the user, to potentially improve the quality of the structural models. The measureable performance and guidance in the present work put emphasis on the geometrical form of the structure as this has the greatest potential to improve the structural performance. The result of the present work is a computational tool for conceptual structural design with a novel human-computer interaction.

## 1.2. Human-computer interaction

Direct manipulation is a human-computer interaction style with continuous representation of objects of interest with rapid, reversible and incremental feedback [36]. Users can directly manipulate objects on the screen using real-world metaphors, which makes the users more engaged with their task and encouraged to further explorations [37]. This is achieved through reducing the perceptual and cognitive resources required to understand and use the user interface [34].

The introduction of different input devices such as the mouse and joystick significantly improved the human-computer interaction of user interfaces that adapted accordingly [34]. Later, when the touch screen was introduced, it had an advantage over all these devices with a very direct method of inputting information [34]. It closed the gap between the human and computer, and the user could literally touch objects on the screen to manipulate them.

There is a wide repertoire of interaction techniques to create direct manipulation user interfaces for 3D applications using 2D input devices such as the mouse [24]. However, since this type of input devices have one degree of freedom less then the 3D user interface there will always exist a need of gestures or similar methods.

Computer games have seen an increase in the amount of novel input devices along with a new style of games to address some limitations of conventional systems [15], e.g. the Wii remote [25], Microsoft's Kinect for Xbox [20] and PlayStation Move [28]. These novel input devices

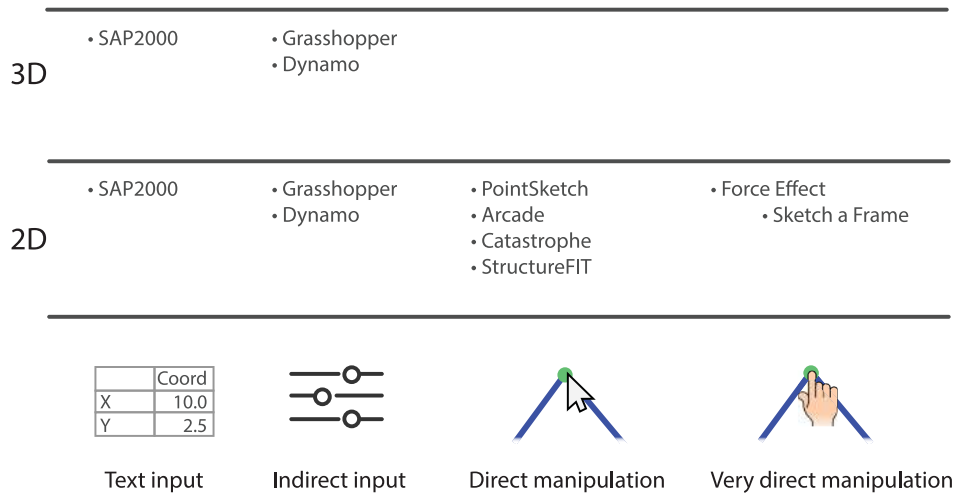
move away from the conventional human-computer interaction to invoke an intuitive interaction that supports the natural human way of working. Games have for long been perceived as fun and engaging, and it has been investigated in many different disciplines if gaming methods can improve the human-computer interaction. In order to create more effective, immersive and engaging learning or training [15]. In computer aided design tools the user experience has been compromised by the engineering design system's step-by-step evolution. The present work moves away from the step-by-step user interface to create an interactive gaming like experience by using a novel 3D input device.

This is beyond the scope of this paper, but interest and development of virtual reality glasses, such as the Oculus Rift [26] and PlayStation's Project Morpheus [29], have recently increased. This type of virtual reality glasses have primarily been developed for games but other fields have also shown interest, e.g. in [8] a virtual reality is used to help students understand complex structural behavior.

## 2. Related work

Multiple software tools for conceptual structural design that deploy truss models have previously been developed. The first two such tools was developed in parallel and released in 2006, named PointSketch [27] and Arcade [19]. In the two different software tools, the user can create a computational model using mouse and keyboard input. Forces can then be applied to the model and the results from the computations are visualized. The two software tools were both developed in academia but industry has shown interest in the concept.

The commercial finite element (FE) software SAP2000 launched a "model alive" feature in 2012 that enables real-time feedback for deformations and forces [4]. The software is developed for use with truss-structures. However, geometrical modifications are made through text input. Autodesk launched a new application in 2011 named ForceEffect [2], which is available both as an tablet application and as a web application. The application is developed for designers to analyze and visualize two-dimensional truss structures. The tablet application utilizes a direct manipulation user interface style where the user can make changes to the model by directly touching the objects. A similar application that further developed the direct manipulation of the interaction is a tablet application named Sketch-a-Frame [1]. This application updates the visualizations of the computational result in real-time as the user make changes to the geometry, creating a very direct manipulation. Another conceptual design tool that can generate structures through interactive optimization is called StructureFIT [21,22].



**Figure 1.** Previous work summarized.

The software tool also has a direct manipulation mode where the user can further explore a generated structure by moving nodes and in real-time see how a relative performance index is updated.

Recently an interactive physics engine was developed to create a user experience inspired by games for design and education [35]. The developed physics engine has been used to create an interactive game called Catastrophe, which aims to teach users which elements are critical to system stability through play.

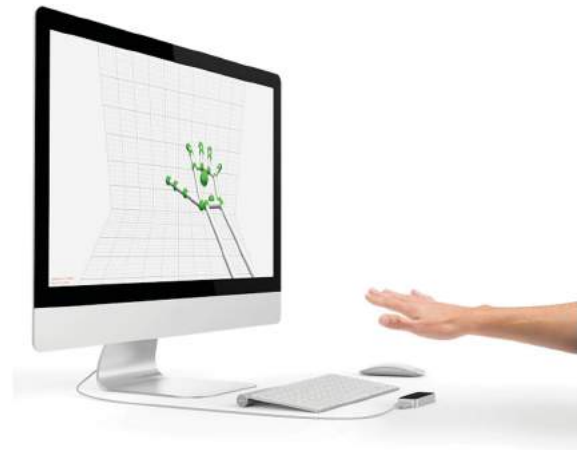
A popular design tool in practice is the parametric modeler Grasshopper [10], which allows the user to manipulate parametric models through the use of sliders. This can be combined with Karamba [13], which is a structural analysis tool, and can then give real-time feedback how the structural performance changes when the input parameters are altered. A tool that implements similar functions is Autodesk's Dynamo [6].

A summary of the evaluated conceptual design tools can be seen in Figure 1, the tools are grouped according to number of dimensions and how direct the manipulation is experienced. Prior to the work presented here, no conceptual structural design tool has before been able to achieve a very direct manipulation for 3D. A very direct manipulation user interface has before only been achieved for 2D conceptual structural design tools. This is due to limitations in the traditional mouse and keyboard human-computer interaction that the 3D applications were developed.

### 3. Methodology

The Leap Motion controller [16] is a novel 3D input device. It can with the use of infrared cameras create a virtual model of a users hands that are in the field of vision

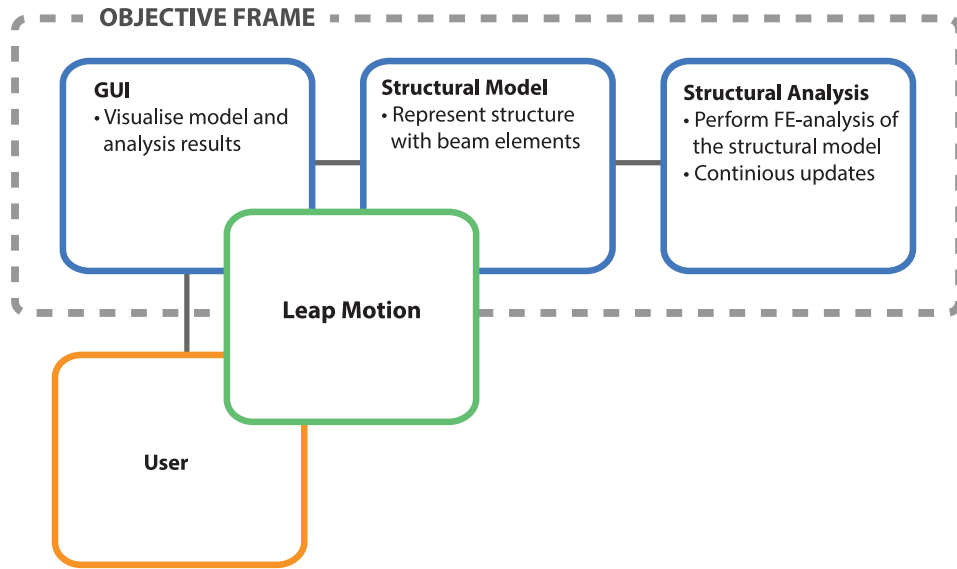
for the controller, see Figure 2. This creates a possibility to allow users to very directly manipulate representations of objects in 3D – which has the potential to improve the human-computer interaction of structural conceptual design applications. An improved interaction in such applications can potentially improve the users understanding of the structural behavior of a model, cognitive engagement in the design task, and encourage further design exploration. The present work shows an implementation with a very direct manipulation for 3D that not before has been achieved for conceptual structural design tools.



**Figure 2.** Leap Motion controller in use.

#### 3.1. Leap motion

A new 3D input device for computers was launched in July 2013, named Leap Motion Controller [16]. By connecting the controller to a computer and placing it in front of the user, it can track movement of fingers, hands



**Figure 3.** Conceptual diagram of how the Leap Motion controller integrates into the existing conceptual design application Objective-Frame.

and tools with sub millimeter precision without any visible latency [16]. A software development kit (SDK) is available and supports most common programming languages [17], which can be used to implement support for the controller into existing applications.

The SDK interprets the data from the controller's cameras and creates computational models of any hands or tools (e.g. a pen) that is in the field of vision for the controller. With the SDK implemented into an application, the computational model can be accessed through the application programming language (API). The API has functions to return the positions and direction-vectors of hands, fingers, and tools in 3D. This can be used to build and visualize a virtual model of a hand or a tool that can directly interact with 3D objects on the screen. The SDK also has built in support for gestures that can be used to call actions. This creates a potential to create very direct user interfaces for 3D, similar to the possibilities that the multi-touch user interface created for 2D.

However, new input devices require that software adapt accordingly in order to be successful [34], thus new 3D input devices are heavily dependent on software developers that can create new novel user interfaces.

### 3.2. Detailed implementation

The work in this paper builds on an existing application that was developed for conceptual structural design named ObjectiveFrame [18] (see Figure 3). The application is developed in the programming language C++ and uses the toolkit FLTK [7] to create the GUI and the matrix library Newmat [30] to perform matrix operations.

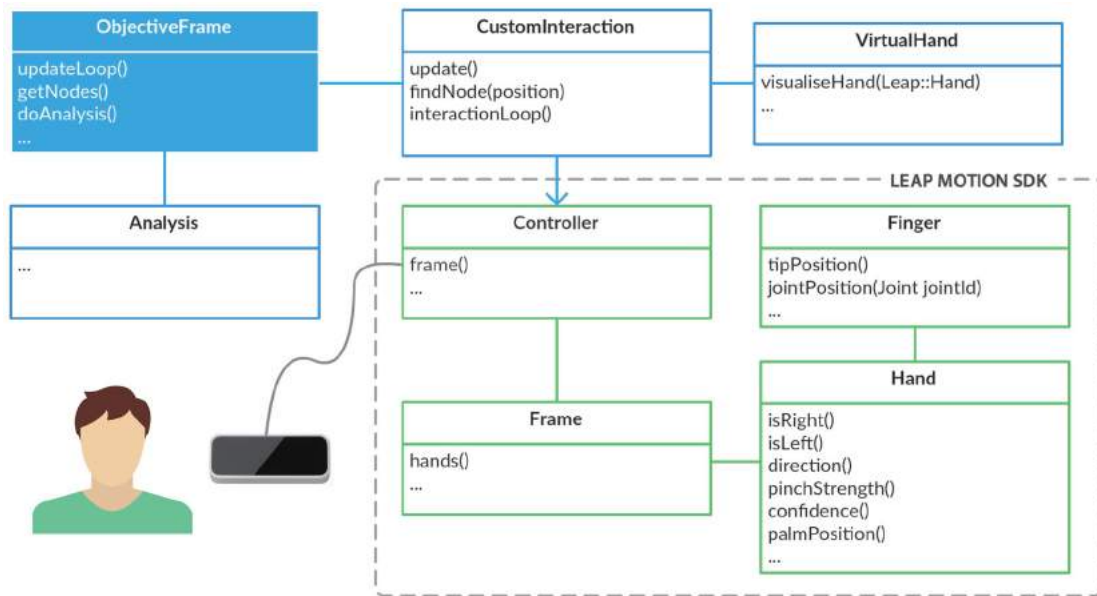
When an instance of the class *Controller* is instantiated the Leap Motion SDK creates a computational model of the objects in its vision field. The Objective-Frame application has an update cycle where the objects of representation are continuously updated. The class *Controller* is queried in each update to get an updated *Frame* that contains information of the computational models.

Three different cases have been implemented in the existing application to demonstrate how the Leap Motion controller can be used in the conceptual design phase.

### 3.3. Direct manipulation interaction model

The data from the Leap Motion SDK is in the developed application used to visualize a virtual model of the user's right hand. The tip of the index finger on the virtual hand is marked with a color, as seen in Figure 6 - the fingertip is used to select nodes in the 3D space. When the index fingertip position is within a set distance of a node, the node is highlighted. The user can then perform a pinch gesture (see Figures 5 and 6) to interact with the highlighted node.

The right hand is used to interact with the structure while the left hand can simultaneously be used to control the point of view, i.e. from where the model is observed and from what angle. Moving the palm closer or further away from the controller zoom out respective in. This is a direct manipulation metaphor for pushing the model away. The palm position can also be used to rotate the point of view around the model by moving the palm sideways. The angle of the hand is used to control the angle of which the model is observed.



**Figure 4.** Diagram of how the Leap Motion SDK is added to the existing application.

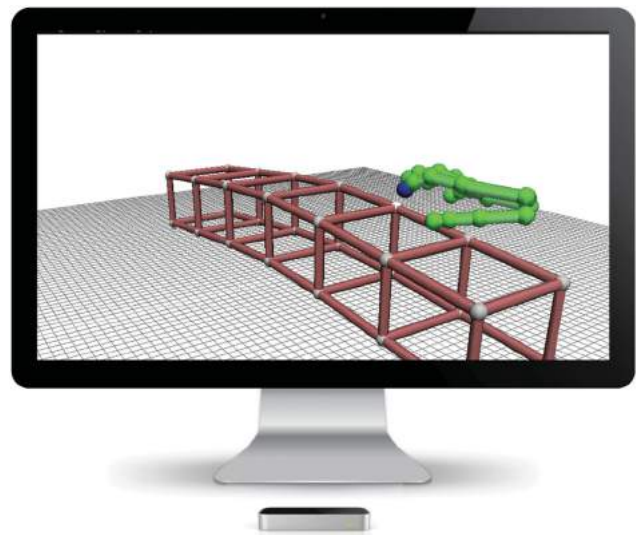
The position of the virtual hand is relative to the point of the view. Thus, when the user rotates the view, the virtual hand is rotated accordingly around the center of the view. This is in line with the metaphor that the user reaches into the monitor to interact with the structural model. The Leap Motion SDK also has a confidence parameter, this is lowered if the view is obstructed e.g. if the left hand obstructs the view of the right hand, this is visualized using the opacity of the right hand to indicate for the user that the view is obstructed.

#### 4. Structural analysis for conceptual design

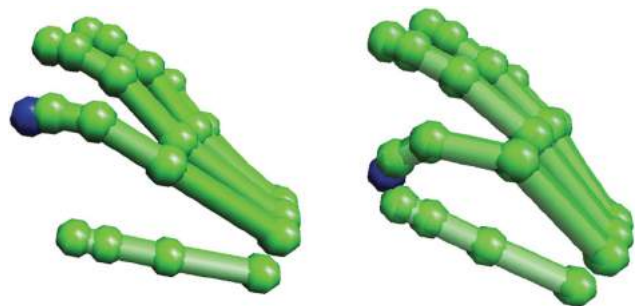
To enable structural performance feedback and guidance in the application, see *Analysis* in Figure 4, numerical analysis methods have been implemented in the application. In conceptual structural design a simple mathematical model such as a truss or a frame is advantageous to represent a structure [32]. The objective is a general understanding of the structural behavior and numerical precision is of less importance. In later design stages, the simple mathematical can be substituted for a more advanced mathematical model for improved accuracy.

##### 4.1. Structural analysis

To enable the application to visualize deformations and normalized structural performance, finite element analysis has been implemented in the application. The application uses 3D beam finite elements that can be used to create frames or trusses to represent structures. Every



**Figure 5.** Montage with image from the developed application.



**Figure 6.** Pinch gesture visualized with the virtual hand model.



beam element has two nodes – which each have 6 degrees of freedom, three rotational and three translational [3]. The structural response is computed using

$$Ku = f$$

Where  $K$  is the global stiffness matrix,  $u$  the displacement vector and  $f$  the force vector. The compliance of the structure is the work (or strain energy) performed by the truss, is the sum of the forces multiplied with the displacements:

$$W = \frac{1}{2} f^T u$$

This can be rewritten as

$$W = \frac{1}{2} u^T K u$$

Ideally, the strain energy is a small number, which corresponds to an efficient structure. To convey how geometrical modifications change the structural performance - the strain energy of the modified geometry is in the developed application normalized with the initial strain energy. The result is the normalized strain energy, a measurement of how well performing the structure is.

#### 4.2. Form finding

The process of designing form-found shapes is called form finding. Either physical models or numerical simulations can be used in this process, where the aim is to find the form for a structure under load where static equilibrium is satisfied. The static equilibrium corresponds to a structure that can support the applied load using only

compression, thus a very efficient structure. For physical models a hanging chain or cloth can be used to find the static.

A number of different numerical methods exist to computationally find the form where static equilibrium is satisfied. The numerical method used in this work is dynamic relaxation, which is a method to solve a set of non-linear equations, invented by Alistair Day in 1965 [5]. The method computes the movement of a structure over time to find equilibrium between the internal and external forces.

In each time step,  $\Delta t$ , the internal forces for all elements are computed from the nodal displacements  $u$ . A residual,  $R$ , can be computed by using

$$R = f_{ext.} - f_{int.}$$

By using Newton's second law the acceleration (time derivative of the velocity) can be computed as follows (at the node  $i$ , in the x-direction, at the time  $t$ )

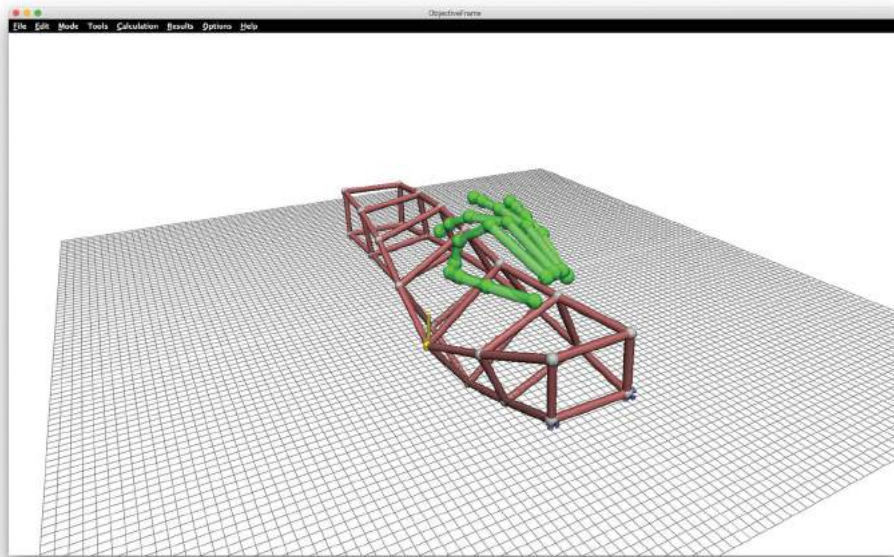
$$R_{ix}^t = M_i v_{ix}^t$$

Where  $M_i$  is a lumped, fictitious mass at node  $i$ . To enforce boundary conditions, the residual is set to zero for the corresponding degrees of freedom. With the time step known the velocity of node  $i$  in the x-direction can be computed using finite difference method

$$v_{ix}^{t+\Delta t} = v_{ix}^{t-\Delta t/2} + \frac{\Delta t}{M_i} R_{ix}^t$$

With the velocity known the updated geometry can now be updated by using

$$x_i^{t+\Delta t} = x_i^t + \Delta t \cdot v_{ix}^{t-\Delta t/2}$$



**Figure 7.** Structural response visualized in real-time.

As the geometry is updated, an iteration is complete and the computations start over, by again, computing the residual. The geometry is modified each iteration until equilibrium between external and internal forces has been reached. Different types of damping can be used such as kinetic or viscous, to get the solution to converge. In the present work, the velocities are set to zero with even intervals to get the wanted dynamic behavior.

## 5. Case studies

The material parameters are not of emphasis in the following conceptual design case studies, however, they will have a minor impact of the result and are therefore presented in Table 1.

**Table 1.** Material properties used – which represents a steel tube

Young's modulus	$2,1 \cdot 10^9$
Area	$3,5 \cdot 10^{-3}$
Second moment of inertia	$5,3 \cdot 10^{-6}$

### 5.1. Case I: Structural response

In this case study a point load can be applied to a structure, the resulting deformations are then visualized in real-time. When a pinch gesture is performed on a node, a point load is applied. Then as the user moves the pinched fingers away from the node, the applied force changes direction and magnitude accordingly. Thus, the

further the user moves the hand from the start position, the larger the magnitude of the applied force is. The structural deformations are continuously computed and visualized for the user. As the pinch gesture is released, the applied force is removed and the structure is visualized in its undeformed shape.

The scaling of the structural response is automatic and relative to the stiffness in the node where the force is applied. The applied force for node  $i$  in the x-direction, is computed as follows:

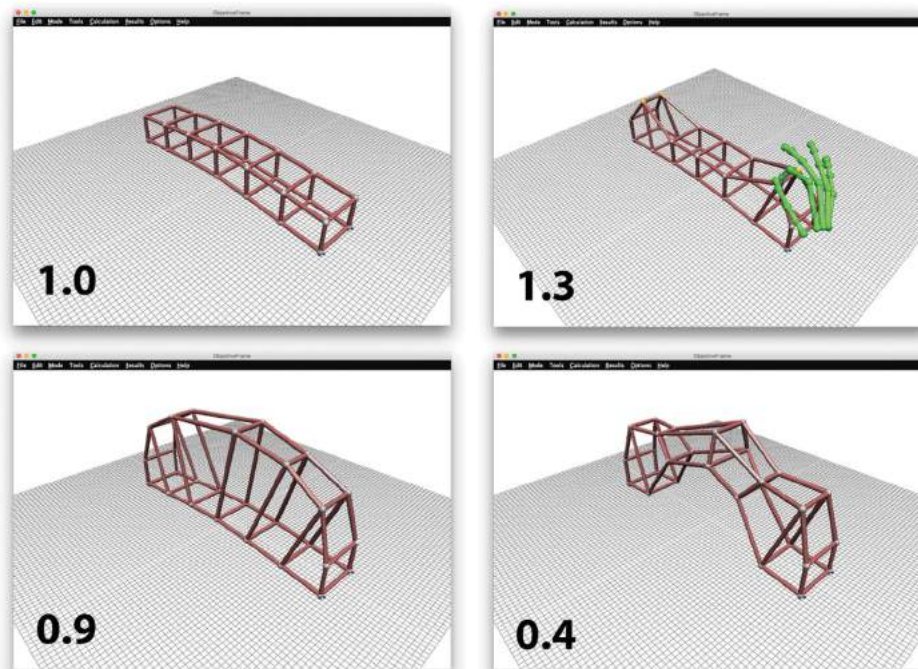
$$f_{ix} = P_{currentx} - P_{startx}$$

Where  $P_{startx}$  is the point the index finger when the pinch gesture was performed, and  $P_{currentx}$  is the current position of the index finger.

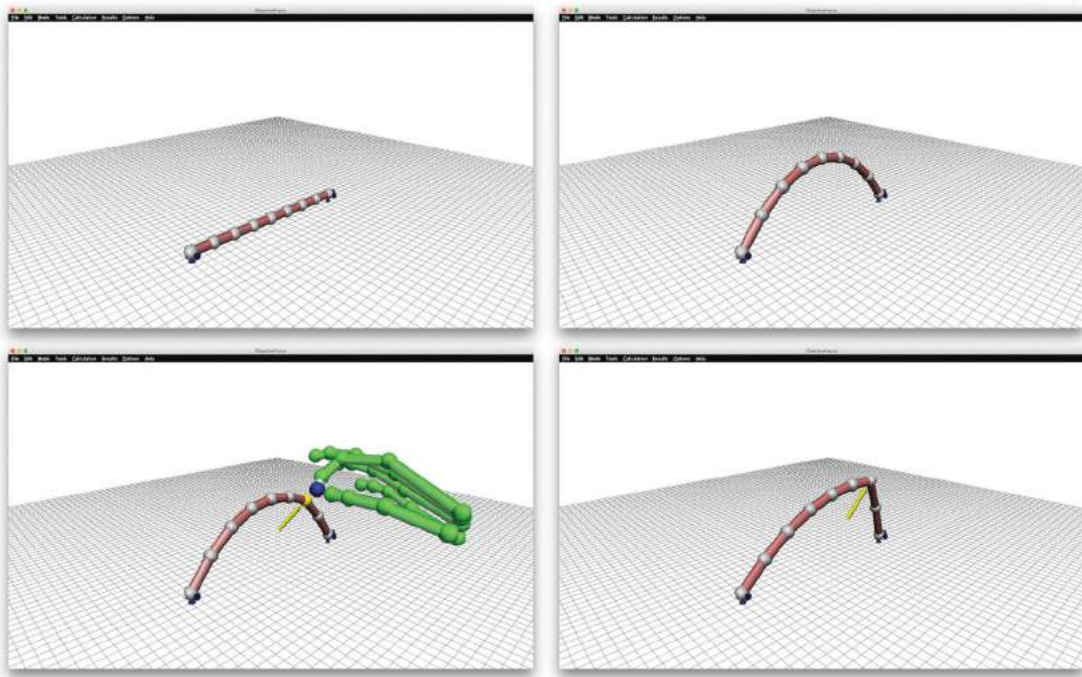
### 5.2. Case II: Performance feedback

For this case, the user can move nodes of a structural model by using the pinch gesture. The strain energy of the structural model is continuously computed, normalized and visualized on the screen for the user. The strain energy is normalized with the initial strain energy, thus the normalized strain energy is initially 1.0, where a lower value corresponds to a better performing structure.

An example of the design exploration process is shown in Figure 8; in this example symmetry along the depth and width of the model is enforced. Thus, when a node is moved three other nodes move to enforce symmetry.



**Figure 8.** Design process with normalized strain energy.



**Figure 9.** Educational example - Upper left shows initial geometry, upper right shows the static equilibrium under negative gravity load, down left shows how a point load being applied, down right shows the static equilibrium for negative gravity load and a point load.

Enforcing symmetry makes the modeling process faster and different designs can easily be evaluated.

### 5.3. Case III: Dynamic relaxation

The dynamic relaxation method has been implemented in the application. In this case, the geometry is computed and updated once in every refresh rate of the application. This results in an interactive application where the user can observe how the geometry is updated and modified until static equilibrium has been reached.

In the following examples, a negative gravity load has been applied on the nodes. The user can then, by using the same interaction as described in Case I, apply a point load to any node. The benefit of using dynamic relaxation is that the geometry will start to converge towards the new static equilibrium even if the static equilibrium was not found for the parent load. This improves the interactivity of the application by following the direct manipulation guideline of continuously updating object of interest. In Figure 9, an example is shown which corresponds to the physical prototype of a hanging chain.

As the designer applies a point load to the structure, the 3D dynamic response is interactively visualized. This can be used for educational purposes, to improve the users understanding of the structural behavior of the model.

In Figure 10, an example is shown where the dynamic relaxation is used to find the form of a structure. The

point load can here be used to move away from the optimal solution [14], to find other interesting sub optimal solutions, which might be more aesthetically attractive to the designer. The point load can also for example represent a supporting column or a hanging installation in the structure.

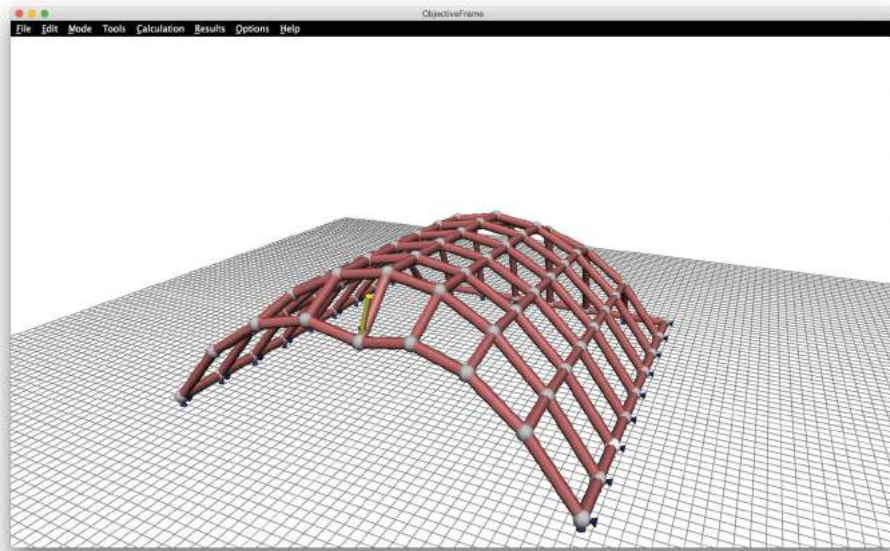
## 6. Discussion

This work shows that new 3D input devices have potential to create very direct manipulation user interfaces for conceptual structural design, previously only achieved for 2D. The human-computer interaction in an existing application is improved, which improves the user's ability to explore different designs. The conceptual design environment is important and it can have a big impact on the final design. This work shows an alternative user interface for development of such tools, which in the future potentially could have a big impact on how we design structures.

The implemented methods aim to improve the designers understanding of both the static and the dynamic behavior. The implemented methods also allow for the designer to navigate the design space, and allows the designer to make trade offs between structural performance and aesthetic.

Hand gestures are used in the application to manipulate from where, and from what angle, the structure is





**Figure 10.** Example of a form found structure using the developed application.

observed. This could easily be implemented in existing CAD software to allow the user no more easily navigate the 3D space.

### 6.1. Summary of intellectual contributions

- Paper includes critical review of existing tools and techniques for design manipulation in conceptual computer-aided design.
- First paper to propose very direct manipulation as human-computer interaction mode for 3D structures, thanks to new 3D input device such as Leap Motion controller
- Paper introduces implemented design tool that allows users to interact with 3D structures through very direct manipulation.
- Paper demonstrates potential applications through three case studies.

### 6.2. Future work

The Leap Motion controller's SDK supports virtual reality glasses, such as the Oculus Rift. Combining the two can create a virtual reality where the user can experience the structure in 3D, interact, and make changes to it using the hands.

This could potentially be developed in a game environment where the structure could be visualized in the intended context i.e. the building site, a game engine would enable real-time renderings of the structure in its context. The designer would then be able to make manipulations, guided with performance feedback, to the

rendered structure. This could improve the conceptual design process, and by doing so, have a big impact on the design process and the final structure.

### 6.3. Concluding remarks

- Paper responds to need for new, more intuitive and natural interaction modes in computational design and analysis
- Very direct manipulation improves significantly beyond existing direct manipulation paradigms prevalent in computer-aided design.
- New technologies like the Leap Motion controller open up unprecedented possibilities for engaging users in the exploration and design of 3D structures, leading to improved understanding of design options and performance in the built environment.

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