INTRODUCTION

Digital communication techniques enable to express the relation between a user and a building. This continuous relationship between the individual and, in general, his environment, is what digital architecture is trying to express (Picon, 2010). This study explores the dynamic nature of the interaction between user and building by relating the user’s experience to the building’s experience. The former is investigated through psychological research or from a phenomenological point of view. The latter is investigated by mathematics and physics. Since Einstein’s special theory of relativity (Einstein, 1905) the description of both experiences have changed. The existence of one space-time continuum influenced the modernist, who coupled the experience of space and time by emphasizing the movement of a user through space (Giedion, 1941). From this point, the user is seen as a dynamic entity. In contrast, buildings are mostly regarded and designed as static entities. Their relation to time and consequently their actual use is neglected, and only a static form is designed. In dynamics, form is only a snapshot and results from behavior which includes time and change. When designing behavior, it is not only about the system’s current state, but also about how it acts. The architect Heatherwick used this way of thinking when designing the Paddington Bridge. He stated: “Instead of what it is, our focus was on the way it worked.” [1]

Change is inherent to dynamics and also an important characteristic of the bit, which is the corner-stone of the digital age. Bits are easy to change and are transported with the speed of light (Negroponte, 1996). Machines use these properties in order to exchange information, and fit in contemporary architecture effortlessly (Shepheard, 2003). Build-
ings struggle to use these new techniques because of their opposing static, atomic and heavy nature. This physical condition is the reason for the importance of the load bearing structure. Schopenhauer (1997) even suggests that the dynamic interaction between support and load is the most important esthetical theme of architecture. The structure shapes the building’s spatial configuration to which the user emotionally relates. In contemporary architecture, structure as an emotional experience remains elusive; a far too abstract notion to be emotionally felt. In this paper, the user is seen as a dynamic load and the relation between user and structure is expressed. By means of a psychological and phenomenological study, it is shown that the user can communicate intuitively via forces. The goal of this investigation is to explore how digital communication techniques can be used to express the fundamental physical interaction with the building. A conceptual design is presented in which the dynamic nature of the interaction directly is expressed and also is incorporated in the physical shape.

**DYNAMIC USER’S EXPERIENCE**

Psychology and phenomenology both investigate the human experience. Visual perception plays a key role in this experience (Von Meiss, 1990). The German phenomenologist Hermann Schmitz (2005) describes perception as corporeal communication. He uses the concept of the felt body with its characteristic corporeal dynamics between expansion and contraction. With his concept of corporeal involvement during perception, he explains how we link what we see to our own body and therefore perceive forces in an object. If we see an inflated balloon we experience intuitively the tension of the skin which reacts to the increased air pressure, because our own body is also characterized by the dynamic interaction between expansion and contraction.

The German psychologist Rudolf Arnheim (1974) also studied (visual) perception. He related physical forces to mental forces in order to explain how we experience the world around us. He states that we know from our own muscle sensations how to handle forces. Therefore, we directly experience the forces in an object. Forces give an event visual expression and endow it with life. He clarifies this statement with analyzing movement which looks dead if it is showed as mere displacement, but comes to life if the moving object expresses the forces acting on it. The human subject is seen as an active dynamic entity that grows, moves, changes, creates and explores. Schmitz and Arnheim both explain that humans intuitively relate to forces and that perception has a dynamic character.

**DYNAMIC BUILDING’S EXPERIENCE**

The building reacts to environmental forces by adapting to them. When experiencing physical forces it will change its shape to withstand them. In common practice, buildings are seen as static entities because they are designed as stiff structures and barely deform. Therefore, structural calculations mostly neglect accelerations and only consider equilibrium. The users are simplified to generalized loads and the way it deforms is ignored. However, it is possible to describe the interaction with loads by using time integration. In combination with Newton’s second law (1), accelerations can be calculated that result from the forces acting on it (2).

\[
\text{Force} = \text{Mass} \cdot \text{Acceleration} \quad (1)
\]

\[
\text{Acceleration} = \frac{\text{Force}}{\text{Mass}} \quad (2)
\]

Implemented in a mass-spring system these accelerations are converted into displacements. This of course, is still a simplification of reality, but more close to real behavior than the static description.

**INTUITIVE RELATIONSHIP**

What can we learn of new wearable digital devices we use to communicate with our environment when designing the ‘user interface’ of a building? The iPhone 4 shows that an intuitive use is very important. It uses, for example, inertial scrolling for making it appear as if something tangible shifts (Isaacson, 2011). So if you wipe over the screen, software
calculates representative virtual forces which stand for the mechanical forces that result if you push an object aside. Instantaneously, the effects of your actions are visible, and you feel that it is you who is making the physical action. As a result of that, communicating with the device is possible as it will give you suggestions as a response to your actions. Normally, when interacting with a building, its reaction remains imperceptible. Communication is impossible, because it presumes two active entities. As the dynamic nature of the interaction is hidden, the relation between user and building is not experienced as continuous, but as separated. When forces, resulting from the interaction between user and building, are expressed; the user could notice the continuity of the relation.

ADAPTATION TO FORCES
Next to direct communication during interaction, long term adjustments can show the dynamics of the interaction. Arnheim (1974) states that the shapes of natural objects are the traces of the physical forces that created the objects. This is because of the direct adaptation that Thompson (1992) mentions next to adaptation via heredity, described by Darwin (1859). For example, bone adapts to mechanical forces and as a result it has a structure which is optimized to the forces acting on it (Cox, et al., 1990). Trees show a similar kind of adaptation to mechanical forces (Mattheck, 1998), but with the difference that cells of wood die and harden, and bone stays alive and completely regenerates.

ADAPTATION IN ARCHITECTURE
Adaptive architecture has many faces. A subcategory is transformable structures. At a small scale, buildings use doors, windows and blinds to adapt to use and environmental influences. At a large scale Calatrava (Jodidio, 2007) and Hobermann[2] have shown in practice that it is possible to fabricate large transformative structures. Research and installations show that the relation with the user is being investigated. For example, the design of adaptable or dynamic facades (Suma, et al., 2007) and installations by Roosegaarde (2011). As techniques are developed and research is ongoing, it is likely that this will lead to more practical applications. The design that is made in this paper focuses more at the conceptual user-related level.

CONCEPTUAL DESIGN
A conceptual interactive design is made that expresses the structural dynamic behavior. Its designed behavior is twofold. A short term effect is implemented that expresses the forces in the structure and thereby is able to communicate with the user. A long term effect is designed that adapts the shape to the forces the user causes in the volume and thereby personalizes the shape. The process of adaptation to forces is investigated with particle-spring systems and is based on the adaptation of bone and trees. Both adapt to loading by reacting locally to stress differences. The structure is transformed by moving the particles from places with low stresses to places with high stresses. The algorithm can be used for every geometry and topology. The procedure is as follows:

1. Setup: geometry is created by choosing particle positions and the topology of springs.
2. Calculation: spring forces are calculated and for every particle the sum of the absolute values of the spring forces in the connected springs is calculated.
3. Adaptation: for every particle weighted displacement vectors are calculated in the direction of the connected particle with the highest absolute sum of the connected spring forces. The position of the particle is changed according to this vector. The equilibrium length of every spring is adjusted with the difference in spring length caused by the displacement vector.

Steps two and three of this procedure are executed iteratively. Figure 1 shows a two-dimensional system that is adapted with this algorithm. For this structure, 9 nodes and 20 springs are generated. The nodes in the upper left corner and in the lower left corner are fully constraint. Every iteration, con-
Constraints are taken into account by deleting the displacement vectors. A horizontal force is applied at the middle right node as represented by the pushing person. The algorithm used to investigate the adaptation process in two dimensions is written in Excel VBA and uses the structural program GSA [3] to calculate the forces by means of a static analysis.

The short term effect is investigated in three-dimensional space, as in this case the interaction with real users is essential. The programming language Python in combination with the virtual reality development interface Vizard [4], is used for this. To calculate the internal forces that arise during interaction with the user, explicit Euler time integration is used to determine the displacements (3)(4). Next, spring forces are calculated (5).

\[ \Delta \text{Velocity} = \Delta \text{Time} \cdot \text{Acceleration} \] (3)

\[ \Delta \text{Distance} = \text{Velocity} \cdot \Delta \text{Time} \] (4)

\[ \text{Spring Force} = \text{Spring Constant} \cdot (\text{Spring Length} - \text{Equilibrium Length}) \] (5)

As the absolute sum of the connected spring forces is calculated at the nodes, the vertex of a connected triangle is colored red by linear interpolation between a lower and upper bound (6). The color red refers to the color the human face gets when lifting heavy objects and results from blood in the upper layers of the skin.

\[ \text{Green and Blue} = 1 - \left( \frac{\text{Absolute Sum at Node} - \text{Lower Bound}}{\text{Upper Bound} - \text{Lower Bound}} \right) \] (6)

\[ \text{If (Green and Blue)} < 0: \text{Then (Green and Blue)} = 0 \] (7)

\[ \text{If (Green and Blue)} > 1: \text{Then (Green and Blue)} = 1 \] (8)

\[ \text{VertexColor} = (\text{Red} = 1, \text{Green and Blue}, \text{Green and Blue}) \] (9)

The swelling nodes refer to Schmitz’ (2005) characteristic corporeal dynamics between expansion and contraction. Sturm [5] used this principle for the installation Breathing Cloud. The nodes are drawn as

![Figure 1](image1.png)

Principle of two-dimensional long term effect. The structure adapts to internal forces that result from interacting with the user.

![Figure 2](image2.png)

Principle of short term effect. The structure expresses its internal forces that result from interacting with the user.
spheres with a size calculated by linear interpolation in a similar way as the color interpolation.

**3D SIMULATION**

A Desk-Cave is used for interaction between the presented conceptual design and real users. A Desk-Cave is a Cave Automatic Virtual Environment operated from a desk. The user can sit behind the desk and is surrounded by multiple screens onto which beamers project the virtual environment (Achten, et al., 2004). A mouse is used for navigation. This environment makes it possible for the user to examine the behavior of the structure. Namely, the visual experience of a building is not characterized only by looking at an image, but by looking around and looking from different observation points (Gibson, 1979).

The algorithm in Python, embedded in Vizard, written for the Desk-Cave, generates a three-dimensional hollow cubic geometry which is built up with nodes and bars. Four non-symmetrically located entrances are created by removing specific bars and adding trapezium walking planes. The cubic volume is raised one meter and has four supports. Because of this, forces that act on the structure will cause an interesting load transfer path. Figure 3 shows renders of the geometry before use.

In Vizard the triangular planes can be switched on or off. Figure 4 shows the structure without the triangular planes.

Every iteration, the algorithm calculates the short term and long term effects. The model only serves to investigate the relation between one user and the structure. Therefore, no relaxation techniques or similar methods to undo some of the deformation are implemented. As a result of this, when used, the structure will contract and after, it will change less in regard to new forces. Cause of performance issues, the maximum and minimum length of the springs is not constraint. This also generates a more expressive long term effect as the structure has more freedom to deform. The user is given the possibility to introduce vertical forces in the volume by walking and horizontal forces by pushing.

By means of a small user survey, the interaction between user and adaptive structure was investigated. The resulting geometries after four runs are shown in figure 5. From observation of the author these four participants all intuitively experienced the forces by seeing the deformations and color gradients when they pushed against nodes. When comparing the long term effects to one another, they stated to recognize the user’s characters.
CONCLUSIONS
During interaction between user and building, both are active, dynamic entities. Humans intuitively communicate with their environment via forces. In combination with communication techniques this can be used to create an awareness of an individual's influence on the environment. A user can relate deformations and color gradients to the forces he exerted. By expressing the forces in a volume a dynamic structural expressivity is seen.

DISCUSSION
Relating psychological and phenomenological research to the way a building responds, is important when designing communicative architecture. An important theme of architecture, the dynamic interaction between support and load, is used in a new way. Communication by means of forces results in that both user and building are able ‘to speak the same language’. Both short term and long term effect, separated or in combination, can be implemented in future architecture. The short term effect, the expression of forces, can be used to create a user-awareness of the dynamic interaction with the building. The continuous relationship between the individual and the building will be visible. In practice, this could be realized with strain sensors linked to LEDs. The principle of the long term effect, the adaptation to forces, can be used to adapt to real use. Like bone tissue, structures could resemble their history of use and possibly self-optimize their shape. In this way an explicit expression of time will arise. Both effects can be realized as a synergy of the physical nature of the building and its possible digital nature. In the future, bits can be directly used to express physical data and therefore enable intuitive communication with their users.
Figure 5
Geometries after use. Different views show long term effects of four users. For clarity the outer and entrance contours are thickened.
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