Bionic building concept

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ABSTRACT: This paper describes a framework for creating a structured series of levels of building automation. It is designed to allow buildings to acquire intelligence about their own systems and equipment and to gradually obtain control of themselves. This allows planners, users, owners and other actors in the planning, construction and use to view and understand the building's operations and performance at many levels. The framework has five horizontal levels and three communication streams. Each level implies a degree of automation with the scale shifting from the mechanization at the bottom to intelligence at the top. The levels describe (bottom to top) the physical object, their representation as data, the history of the data, the processes to analyse and model the histories, and at the highest level, the ability to learn from this analysis to predict, model and plan future building behaviour. Information moves among these levels in an upstream path as well as in a downstream path. The upstream path describes how sensor information is curated to create logs that, using the IFC structure, create semantic histories. In the downstream path, the histories are measured against simulations and model-based predictions to create use-models and potential event sequences. The event sequences then become the instruction sets for the actuators and equipment in the building. Once these are carried out, the effects then feed the sensor data back upstream. In this way, a cycle of information both upstream and downstream feeds a system that can learn. The paper also describes the third stream of communication. This, at each level of the framework, shows how information given to people can be categorized in a scale of increasingly sentient perception. This denotes how the different levels allow users to perceive the building as a purely mechanistic process at the lowest level and as a sentient being at the highest level.

KEYWORDS: BIM, Intelligent Buildings, Human-Building Interface

INTRODUCTION

The idea of learning from nature is not new to architecture. The idea of a 'bionic building' was explored in (Yuan et al 2017) by comparing conventional building systems to analogous ones in nature. The study, however, did not go so far to discuss the implementation of the concept. This paper describes the components of how to implement the intelligent functionality of an intelligent building. The term intelligent building itself has been used since the 1980s as is discussed in (Wong et all 2005) and could be said to have gained attention as a widespread concept with Fritz Haller's 2nd Symposium in 1991. (Friedrichs 1991)

The Bionic Building Concept described here is a framework that defines several layers of building component interaction and the informational relationship between these layers. The components are also separated into distinct upstream and downstream pathways which controls the flow of information. This framework enables individual advancement of technologies in each area to proceed independently of each other while maintaining a consistent flow of information. In essence, the framework enables individual progress without having to reconfigure the entire system. The goal of the Bionic Building Concept (BBC) is to enable machine learning to develop in building control systems without having to design the intelligence from the start. By configuring the framework in this way, intelligence can emerge from behaviours and a 'learning building' can be developed as individual advancement in technology and/or price arise.

The paper first describes the framework and its constituent parts and how they relate to each other. This is followed by a brief description of the implementation of such a system including the training, trust and hand-over of control to the BBC system.

1.0 BBC FRAMEWORK: LAYERS AND STREAMS

The Bionic Building Concept is defined into five layers organised into two main streams of information (upstream and downstream). A third stream of information moves horizontally and represents the human -computer interface that is available at each layer of the framework. See Figure 1: BBC Framework. In essence, the BBC is a response to the question as what to do with all the sensor data created in a "real-time BIM" system (Russell, Elger 2008).

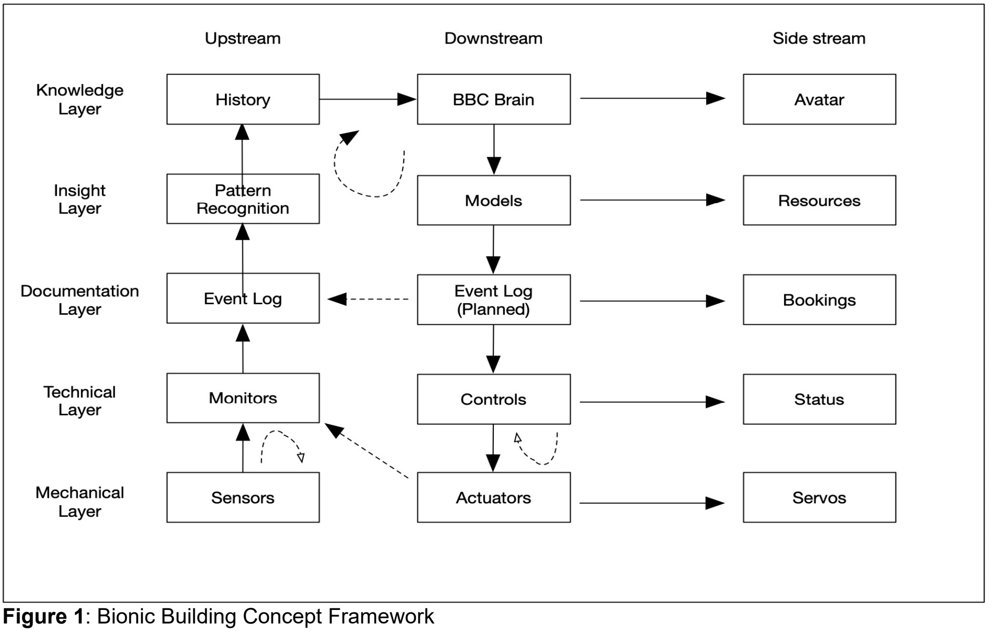

Figure 1: Bionic Building Concept Framework

1.1 BBC layers

The Bionic Building Concept is organised into 5 layers. While these could be mapped onto the 7-layer ISO network model (Reference), for the purposes of this paper, this mapping is ignored. The BBC Layers are labelled from bottom to top: Mechanical, Technical, Documentation, Insight and Knowledge. These layers are described in the following points.

- Mechanical: This layer describes the physical technical installations in a building. They are made up of two primary classes of objects: Sensors and Actuators. Sensors provide data to the system and send it upstream for processing. Examples of these are temperature, CO2, light, motion and other sensors in the building. Actuators are the mechanical devices that respond to instructions from the BBC framework. These can be vents, heating, cooling, lighting and other installations. Often, a single technical installation will contain both sensors and actuators, but for the logical description of the BBC framework, they are considered separate entities.
- Technical: In principle, this is the layer that converts actions into bits and bits into actions. This is kept as a separate layer from the Mechanical layer as not all sensors are solid state devices. Additionally, there is the possibility to place plausibility check at this layer in order to prevent erroneous data going upstream or to check that undesirable commands are sent to the mechanical devices.
- Documentation: This layer is the repository of data. It represents the bulk of the information in the system and is the basis for using machine intelligence. It is also the layer that can connect to other systems at a 'database' or ODCB level of queries and understanding. In the downstream side of the documentation layer, it describes the planned actions for the building, which will be essential during the training and trust phases of implementation.

- Insight: The insight layer is where pattern recognition and initial analysis of the documentation layer takes place. It is, at first a plausibility filter to find outliers and other spurious data. It also serves to highlight where potential 'insights' could be in the data. In the training phase, these insights will be reinforced through human confirmation thus seeding the semantic understanding of the Insight layer. On the downstream side, the Insight layer is a testing ground for potential decisions from the layer above. Different models are used to test potential actions and verified before being passed down to the Documentation layer.
- Knowledge: This is the highest-level layer. On the upstream side, the knowledge layer contains a semantic understanding of past events called the history. This sums up the correlations identified in the Insight layer to describe the behaviour of the building. It serves as the basis for the BBC Brain, which lies at the heart of a machine learning system. At the top of the downstream side is a component identified as the BBC Brain. This is not necessarily any one form of neural network or brute force stochastic mechanism. In principle, any artificial intelligence process can be placed in this position and indeed, it is the idea of the BBC framework to be able to exchange one process or technology for another in any part of the BBV framework.

1.2 BBC streams

The BBC framework has three streams of information: Upstream, Downstream and Side stream. These streams describe the flow of information from the physical position of mechanical systems to the higher-level semantic description of what has and should happen in the building. The side stream will be addressed separately as it describes how the state of the framework can be understood by a human, which has implications for the training and trust phases of the system. The streams are described as follows:

1.3 Upstream information

Mechanical devices, be they doors, windows, thermostats will all have an electromechanical method to convey their position or state to the Technical layer. In some instances, this could be a camera set to look at a mechanical dial. In other instances, it could be a solid-state sensor such as an accelerometer or light sensor. In most cases, the signals will be sent to the technical layer in predefined amounts and frequency of information (i.e. a temperature reading once a minute or the state of a window upon request).

Once the information is sent to the technical layer, it is first checked for plausibility. This means that data that is out of range or consistently set at one value can identify possible failures or calibration problems with the sensors. This is vital to the ability to glean knowledge at the higher levels of the framework as filtering 'bad' data is time consuming and can lead to false insights. Exact procedures to deal with unacceptable data will depend on the sensor and the context. High CO_2 levels should require immediate inspection to ensure occupant safety whereas reading of zero light during the daytime will need a timely maintenance, but not emergency services.

From the Technical layer, the information is sent to a log at the documentation level. At this level the data is logged according to time, position, device type, state, value and time. Ideally, each device will be tagged with Industry Foundation Class (IFC) classification so that the pathway to a semantic understanding is quicker. However, even if no IFC data is included with the data passed on to the Documentation layer, its position, type and time will allow the layer above to filter and process the data.

At the insight layer, the data is pulled up to this layer, not pushed. The insight layer is essentially a combing or 'spidering' of the data stored at the documentation layer. The insight layer is made of processes that scan the documentation layer looking for patterns that trigger recognition according to their algorithms. These patterns are then passed on to the layer above to create a semantic history of the building.

At the top level called Knowledge, the building's insights or patterns are combined with other information to form the Building History. This is a combination of what did what when, what happened where when, and what happened anywhere else when. Thus, the actions of users, the actions of the building itself, as well as calendar data, weather data and any other external information deemed useful is combined into a semantic history. This history provides the high-end fodder for the Bionic Building Concept brain.

1.4 Downstream information

Starting at the top of the downstream information stream, the Bionic Building Concept brain accepts the semantic history at the top of the upstream information. The BBC brain is not designed to be any particular flavour of artificial intelligence, but interchangeable between neural networks or any other current or future variation of machine learning. At the initial phase, the BBC brain is actually a human being. There will need to be a training phase in the implementation of the system and so, for all intents and purposes, the initial BBC brain is a human one. Nonetheless, as AI increases in its scope and more buildings acquire knowledge, the assumption of the BBC brain by AI should be possible.

Decisions as to how to act and react to the information in the BBC history is passed down to the Insight layer to test against models. These models can be physical or other kinds of models. Weather predictions, the thermal transfer through the facade, the behaviour of occupants and statistical data according to calendar dates (are Mondays particularly predictable?) combine to provide an initial test of possible actions to be taken. If the models verify that the potential decisions will achieve the goals (i.e. remain in a temperature/humidity comfort corridor), these instructions are passed down to the documentation layer.

At the documentation layer, the instructions deemed appropriate by the BBC brain and tested against models are put into an event queue, which is essentially the instruction sets for each of the physical installations connected to the framework. In some cases, these will be instructions for a servo (i.e. open a vent). In others they may be instructions sent to people to carry out inspection or maintenance tasks.

1.5 Learning

Once the calendar signifies an event is due, it is passed to the Technical layer. As in the upstream flow of data, the technical layer serves as a stopgap for erroneous instructions that fall outside of acceptable ranges. The layer also checks that the devices are able to receive the data. The technical layer then passes on instructions to device or the service.

At the mechanical layer, the electrical motors then open or close vents, turn on or off lighting and signal maintenance teams to carry out their work. Signals that the event was successfully carried out then are sent back upstream to become part of the BBC history. The feedback can be instantaneous (lighting) or take days (maintenance). Indeed, the variation in timing of data and feedback is one of the biggest challenges in managing the BBC information within the framework.

1.6 Side stream information.

In addition to the upstream and downstream flow of information, there is also a 'horizontal' stream of information at each layer. The side stream information is to convey what the BBC system is doing at any given layer. This is a Human-Computer Interface (HCI) issue in and of itself, but a brief description of the principles is included here. The issue of HCI is not essential to the proper operation of the BBC system once it is up and running, but is necessary for trust that the system "knows what it is doing" in order for control to be passed on to the BBC system.

The BBC system can be understood on different conceptual premises depending on which layer it is being looked at. Each layer has a different interface that reinforces the concept of that layer. See Table 1: Building / Layer Interface Reference.

Table 1: Building / Layer Interface Reference

BBC Layer	Concept	Interface	Technical Implementation
Knowledge	Building as a Sentient Being	Avatar	Conversational
Insight	Building as a Phenomena	Behavioural Animation	Observational
Documentation	Building as a Resource	Calendar	Descriptive
Technical	Building as a Snapshot	Status Lights	Green Lights
Mechanical	Building as a Machine	Switchboard	Query-Based

1.6 Side stream interfaces

The concept behind the side stream interfaces is that at each layer, it is necessary to understand the BBC in a different way. Starting at the highest level, the building can be considered to be a sentient being, a physical phenomenon, a resource, a set of status lights or a machine with certain states. Each concept requires a different kind of interface and while the final design of each layer has not been completely defined, the rough outline of each interface is described below.

At the highest level the building can be thought of as a sentient being. This implies that communication is possible and so the interface will have to be conversational in nature. At worst, this is the 'Star Trek' interface where people talk to the building and it responds conversationally to answer questions or inform the occupants of decisions or other pertinent information. In cases of emergency, this can be more helpful than a simple siren. In other cases, a discussion about temperature and its effect on energy efficiency could help to encourage better user behaviour in the building. In any case, when the building is considered to be intelligent, the interface must reflect this, whether the discussion take place with verbal dialogue or a chatbot-like interface.

At the Insight layer, the building can be understood to be a physical phenomenon, much like a hurricane or any other complex system with emergent properties. This allows us to model behaviour and fine-tune these models based on the accuracy of past predictions. This implies that in terms of an interface, the understanding of the building should reflect this. Thus, the HCI at this layer should provide animations or other visual representations of what has and is likely to happen to and within the building.

At the documentation layer, the building can be understood to be a resource. This means that it has certain attributes that are useable in certain numbers at certain times. Thus, the interface at this layer resembles a calendar or booking system defining which assets are used when. This interface can be used in the past in terms of histories as well as in the future in terms of planned use of the building's components. additionally, this layer is where parts of the building combining many components (i.e. rooms) can be booked collectively.

The Technical Layer depicts the building as set of monitors and controls. The interface at this layer considers this to be a representation of the building's status. The depiction can be considered to be one where an overall status is possible, but then in deeper depiction upon request.

The mechanical layer sees the building as a set of mechanical components and is akin to the 'control room' effect of every component having a status (on/off, open/closed, 20%, etc.) This is the lowest technical level and simply sees the building as a machine.

Depending on the situation and the need to know which kind of information, the interface should be able to switch from one layer to the next. For example, if in a voice-controlled wish for more light, this is not possible, it should be possible to drill down through each interface to finally discover there is a mechanical fault, if necessary. Ideally though, the desired interface will be as high in the layer hierarchy as possible.

1.7 Stream shortcuts

In addition to the upstream, downstream and side stream information flows, there are two 'shortcut' flows that should be mentioned. Firstly, at the level of the Technical layer, there is an implicit shortcut or feedback loop that filters out-of-range data either coming from or going to the physical components. Usually, these will be part of the component's internal construction, but for the purposes of the framework, constitutes a separate information shortcut loop. Secondly, there is a shortcut loop between the Insight layer and the Documentation layer. This shortcut loop is there to allow the BBC brain to test various options.

Testing options is essential for the system to be able to learn without having to actually test this in the real world. The timing of some of the events in the Documentation layer will not need to made in real-time. This means that given the time and computational capacity, the BBC Brain will be able to weigh alternatives against each other through the Insight layer and test these against each other. Until such time as an event needs to be executed in the event calendar, the BBC Brain then can search for better solutions and replace these if they are found.

Secondly, testing without actually implementing an action at the Technical layer is how the BBC system will work for its initial life. Once a building design has been planned, it is possible to create the BBC system without having it connected to an as-yet unbuilt building. Thus, given that the models are accurate and a supply of reasonably simulated data on the upstream data flow, the BBC Brain can 'run' the building for many years ahead of its connection to the actual physical building. This will be essential in the implementation phase where modelling will be tested against reality, the BBC system can be guided and trained and eventually entrusted to autonomously run the building.

Additionally, it is possible at the Technical layer to do some 'pre-intelligence'. In the human visual system, edge detection of objects is actually 'calculated' in the retina, even before it reaches the cerebral cortex. (Marr 1982). By the same token, some of the intelligence can be delegated to the lower layers. In some cases, it has been shown that given knowledge about the topology of their logical networks, sensors are able to identify themselves within a BIM model. (Moellering 2017)

2.0 BBC FRAMEWORK: IMPLEMENTATION

The Bionic Building Concept framework is set up to be modular in that technologies within the components of the framework are interchangeable so long as they respect the information streams to and from each component at each layer. This allows 'virtual' components to be used in place of any component of the system. The virtual components can be simulated data streams or even human beings. For the system, the BBC framework will still function as long as the information streams are respected.

In implementing the BBC system, there are five distinct stages in order for the building to control itself autonomously: Development, Virtual Training, Real Training, Trust Building and Autonomy. See Figure 2: BBC Implementation Phases.

2.1 Development

The BBC system is conceived so as to allow a gradual implementation of the BBC as more experience is gained by the system and more trust can be put into the system. This is also a reason for the modular framework: it allows the gradual introduction of autonomy. In the first phase, the Bionic Building Concept framework is put together and the interfaces between the modules is defined. In some cases, these are ODCB SQL queries and statements, in others, it is merely the reading of a defined data stream (i.e. sensor data). Once the components and their interfaces have been defined, the system can be tested in whole or in part by relaying information in the different information streams.

In its initial phase (development), the most crucial part is the upper two levels where the testing of patterns is measured against predictive models. In fact, without even knowing the geometry of the building and simply using the spatial relationships, it is possible to pre-train the system and to test its components with each other. See Figure 2: BBC Implementation phases.

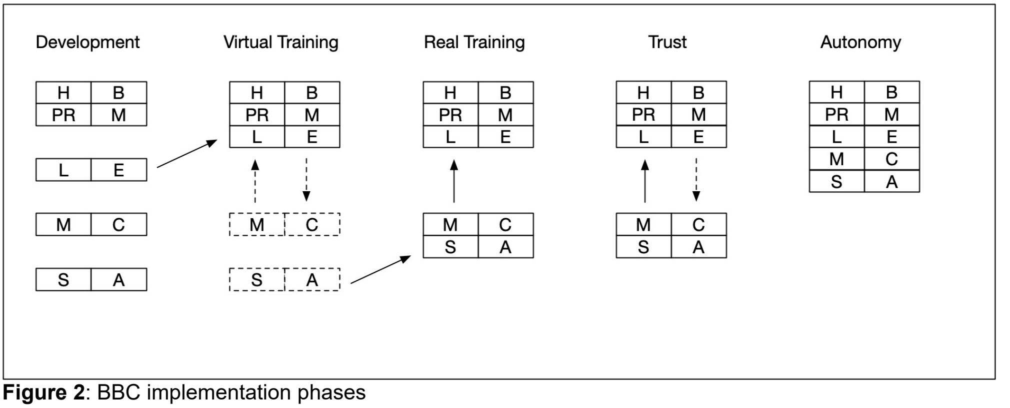

Figure 2: BBC implementation phases

2.2 Virtual training

Once the geometry and other technical aspect of the building are known, it will be possible to start to train the system. although the physical aspects are not yet built, by using historical weather data, assumptions of building component performance and models of user behaviour, artificial data streams can be simulated to 'train' the system to understand and look for patterns in the documentation layer. In fact, because the streams are artificial, the reliance on actual time and periods of data being sent from the technical layer is absent. As a result, it is possible to run the virtual training at an accelerated speed, limited only by processing power and the total time available.

2.3 Real training

After the completion of construction, the technical layer will be coupled with documentation layer in the upstream information flow. This will allow the BBC brain to accept real information from the technical layer including real sensor and mechanical information. Additionally, within other components (i.e. upstream Knowledge layer: History), it will be possible to allow experience humans to adjust and fine tune the semantic information leading the BBC brain to make better suggestions. In some ways, this will beget a new kind of role or employment opportunity: the "Building Whisperer".

2.4 Trust building

Once the BBC system starts to encompass real-world and real-time information into the system, it will start to produce potential actions for the Event calendar in the Documentation Layer. By comparing these to predicted behaviour and to the experience of the Building Whisperer, it will be possible to build confidence that the building would do "what a normal person would do"' Indeed, one of the challenges in building trust is to understand why the building would choose to NOT do something a 'normal' person would do. This is where the side stream interfaces become important. It is hoped that eventually, the BBC system will suggest non-intuitive actions which will result in efficiencies that humans might not have discovered. It will thus be essential to understand why this is so and the side stream interfaces will help at every level to explain the BBC's reasoning and intentions. Failing to do so can arose suspicions as to the BBC's logic and intentions, possibly even suspecting evil ones as in some science fiction (Kerr 1995)

2.5 Hand-off phase

If the BBC System produces actions that are sufficiently consistent and aligned with expectations of building performance, it is possible then to connect the downstream information flow to the Technical layer. Once this is done the BBC system becomes autonomous and its own positive feedback loop. To be sure, the trust is not a single decision and the continual availability of the side stream HCI information will allow people to monitor the system as a whole, as well as the performance of any individual components. As has been shown, the more complex a system is, the more effort is needed to instil trust (Bartneck 2009). Furthermore, as future technologies become available, it is possible to exchange these within any component in order to improve the overall performance of the BBC system

3.0 LEARNING AND TEACHING BUILDINGS

The first BBC system will likely be slow, obtuse and need a lot of coercion in order to become truly autonomous and trusted. However, as more and more buildings use this kind of system, a wealth of data of use, action and their effects will inform future versions and instances of the BBC system. Thus, when a new building is planned, the data from previous experience can be used to seed the virtual training phase thus accelerating the entire learning phase of the building. What is more, if new actions arise from the analysis at the Insight layer, these can be propagated to older instance of the BBC to 'upgrade' the intelligence of all systems.

By this way, it is envisioned that the Bionic Building Concept can seed and propagate best-practices of artificial intelligence and best-case strategies for managing buildings across the entire building stock. This, while interesting in in itself not the reason for pursuing this. The need to radically reduce the resources required to provide habitation and shelter for humanity is under immense pressure from the side of climate protection and the sheer numbers of additional people who will need shelter in the next 30 years. The numbers state it clearly. We want to reduce by half the carbon footprint of humanity, all the while creating habitation (of good quality) for an additional 40%. The numbers mean that we need to increase our efficiency by a three to fourfold in order to meet these goals. It is likely the case, that systems like the Bionic Building Concept will provide the framework to achieve this using an incremental and interchangeable methodology of incorporating the newest technologies to improve where possible.

4.0 Outlook

The current implementation of the Bionic Building Concept is dependent on the quality of the data as machine learning can only be implemented using large numbers of high-quality data. creation of an Open-BIM policy will be essential if current artificial intelligence methods are to be used. Efforts are underway in the Netherlands to create a database of IFC information about buildings in order to meet these requirements.

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