**ModWall** – a Morphological Boundary Concept for Pig Stable Design Based on ModularRobotics.
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**Abstract**

This paper describes the preliminary deployment of **ModWall**, a morphological boundary concept for pig stable design based on novel actuated modular wall elements. Each module contains simple wall pieces hinged to a central infrastructural column, which is turn-able round a single axis by means of actuation. This infra-structural column provides electricity and actuation of wall elements and integrates each modular element into an overall ambient interface with integrated sensor systems to act fluently with the changing behaviour of the users. Several problems in pig production today relate directly to the logistics and the life-cycle of pigs: 1) the time consuming and frequent relocation and separation of pigs according to stall cleaning, production flow, driving out of slaughtering pigs and animal welfare, and 2) the need for fixed stalls of varying sizes for easier maintenance and simple accommodation of pig growth. Based on a background in intelligent buildings systems and robotics, we show how **ModWall** as a system concept can be applied in future stable designs to resolve some of these problems in an intelligent and presumable cost effective way.

1 **Introduction**

The modern production units within pig production have been optimised primarily as regards to area and productivity within a static framework of stall design, but have not yet been implementing the potentials of robotics combined with the detailed considerations for interactions between animals and robots and the aspects of animal welfare. Through the innovation project, StaldTek1, The Danish Technological Institute, Centre for Robot Technology, together with both commercial partners and research departments, have pointed out a series of key areas of development. These include the requirement of new intelligent building solutions and robot technologies to: a) reduce the time consuming task of moving and separating pigs of different age, gender, size and health condition, b) to integrate more hygienic and environmental cleaning and slurry systems, and c) to improve the working environment of the staff and the health and natural behaviour of pigs.

In this paper we present the preliminary research results of a new morphological boundary concept we have termed **ModWall** – a contraction of the words **Modular** and **Wall** – which is a first step towards fulfilling these tasks. The concept offers a flexible system-level design solution providing an alternative to the traditional static layout of stable space while facilitating interactions between environment, humans and animals to ensure better work conditions and welfare. This is accomplished in part by creating a stable layout that through the use of modular and individually actuated wall elements becomes a morphological boundary structure capable of dynamic real-time re-configuration, and in part by augmenting the environment with sensor and actuator systems to control this morphology based on interactions with animals. Depending on the physical realisation of the wall elements, structures like stalls and pathways can be adapted to the current needs of both staff and animals by facilitating automatic relocation of pigs to support, for instance, better cleaning of stalls, individual separation of animals based on physical parameters (eg. weight, size) and isolation of sick animals. This will help rationalise indoor pig farming not only from an economical point of view but also by alleviating the physical strain on the staff whilst actually increasing the attention and care of the individual animal. These factors are all essential in maintaining a sound pig production in Denmark and the rest of EU where firm demands on pig welfare exist and where staff is hard to find due to potential physical attrition.

To illustrate the concepts of **ModWall** we will in this paper focus on a single application: the challenge of selecting, relocating, separating and in the end driving out around 220 slaughtering pigs from the fixed stables to the transportation truck. This process is traditionally a highly stressful and mostly time-consuming process, where the specific pigs need to be selected according to weight, separated from the rest of the pigs, and relocated in a new temporary space until the transportation truck arrives. The process of relocating the pigs from the temporary space to the truck can be at different times of the day and night, and therefore also involves different degrees of manpower and facilities. The situation is sketched in Figure 1 where an imaginary static stable layout is used. However, rational-

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ising this challenge is essentially a matter of providing a sufficient environment where the pigs are gradually stimulated to relocate themselves as well as distracted to not fight internally. Additionally it involves a very detailed scenario for how different building effects like light, sound and experience of static materials are staged together with the dynamic effect of a modular robot to support the overall flow of pigs. We will in the following sections show how this can be accomplished using *ModWall*.

Figure 1: *Left:* The figure shows an imaginary stable with a static wall layout. Pigs are led by a worker (large dot) to one of two different stall areas depending on their weight. The filled dots indicate pigs ready for transportation and the open dots indicate the ones not yet ready. *Right:* The transportation truck has arrived and a worker is leading the pigs ready for transport through the gate to the truck. Another worker (or perhaps the same on but at a different time) is moving the rest of the pigs back to their original location.

The structure of this paper is as follows: Section 2 describes the state of the art as an introduction to the intersections between the application of interactive building systems and modular robotic within animal production units. Section 3 describes the concept of *ModWall* through its components, and Section 4 exemplifies one practical application case of the concept. Section 5 sums up the results in the conclusion and offers some direction for future work.

## 2 State of the Art

The application of the *ModWall* concept to the domain of farm design and dynamic pig stables essentially involves a radically new approach to the future of farming, which integrates the mutual benefits of robotic systems and interactive buildings. It rests on the basis of new post-agricultural concepts, which incorporates the complex organisation of animal production processes into an adaptable building interior to work fluently with the changing behaviour of humans and animals [1]. This transformation to new more adaptable production systems essentially involves the design of buildings as performative systems stemming from two different directions within architecture and intelligent buildings [2]. On the one hand buildings as static objects impose certain affordances on the users, which affect the specific behaviour inside the building and the general experience of the space [3]. This essentially implies that the users of a space are affected by the basic functional, semiotic and phenomenological organisation of the space. On the other hand the interactive effect of intelligent building systems implies a real-time reconfiguration of spaces in accordance with a change in user behaviour [4]. This essentially involves the integration of interactive systems having a bi-directional communication between the user and the building [5], which opens up the building for individual configuration and more dynamic scenarios of use.

The study of intelligent building systems and adaptive behaviour was initiated with second-order cybernetic systems taking into account the observer as participant in the system [6]. At the same time it follows from a long tradition of high-tech architecture to gradually develop more sophisticated modular building elements, initially as a mechanistic vision and a passion for new technologies [7]. Each of these traditions have developed into respectively more advanced intelligent building systems with the purpose of optimising e.g. ventilation principles, light and energy consumption depending on building usage as well as more cost-effective industrial building components providing cheaper and faster construction processes. However none of these of directions have yet integrated the lower-level mutual benefits of having more simple but intelligent modular elements which respond fluently with animal behaviour. This essentially involves a more thorough research into the performative acts happening between robotic interior and animal behaviour, as well as how different morphologies of spaces can be developed from simple modular elements.

Recent projects look into responsive environments acting in a perpetual feedback with organic processes [8, 9, 10, 11] but this needs to be applied for more practical use in order to integrate in a pig stable. Here the constraints of the existing building environment, the specific needs of the involved human and animal actors and the development of the modular robot elements need to be adjusted accordingly with the very specific scenarios of use.

The research field of modular robotics has been fast growing in the past decades and a variety of modular robots are now in physical existence, for instance, the M-TRAN [12], the ATRON [13] and the Odin [14] robots, to mention just
a few. One of the key motivations for modular robotics is versatility [15] which has been sought and implemented in various ways, for instance, through their geometric arrangement (lattice, chain/tree, or mobile architecture), their control architecture (centralised or distributed), their control execution type (in series or in parallel) they way they reconfigure (deterministic or stochastic), the mechanical design (homogeneous or heterogeneous), the number of Degrees-of-Freedom (DOF) each module has, whether their system motion is planar (2D) or spatial (3D), and whether they are self-reconfigurable or not [14, 15] – the length of this list gives an impression of the vast number of possibilities.

However, in spite of the abilities of modular robots today and though the advantages of their use are apparent, the definition of a real-world “killer application” for modular robots has been somewhat elusive, as described in [15]. Space Exploration and Bucket-of-Stuff are mentioned as possible real-world applications, but we have not been able to find published evidence of their physical realisation. We therefore firmly believe that applying our ModWall concept – though only on a conceptual level – in a morphological boundary concept for pig stables, is novel in nature as this application will guide the entire design process and hence also the final manifestation of its modular robot.

3 The System Components of ModWall

The ModWall concept is a system-level concept which comprises actors, modular robots and environmental components all mutually interacting to ensure the desired behaviour of the actors. We visualise this setup as shown in Figure 2 and give a brief introduction to them in the following sections.

3.1 The Actors

The actors, often referred to as agents within robotics, are both the human and non-human actors, which modify the state of the system [16](p. 71). The modular robot is an actor, but as a starting point the behaviours of the human and animal users of the system are the most important actors to keep in mind, to define the initials goals of the modular robot and its integration into the building environment.

3.2 The Modular Robot

The modular robot is comprised of several modules arranged in some formation each having some means of actuation and some elements to actuate. A module can therefore have several Degrees-of-Freedom and depending on its realisation comprise both rotational and prismatic actuation in several dimensions. The main function of the modular robot is to provide a morphological boundary that works in concert with the actors and the surrounding environment.

The modular wall system, the actuation principle and the electronics and software is based on the concept of modularity positioned in a refined grid to integrate it with the environment. It is a concept which makes is easy to interchange and maintain the individual elements, at the same time as it fits into an overall logic of having a simple expression in use within the environment. The control algorithms are based on a distributed architecture (possibly multi-agents) which allow for an overall collective behaviour based the individual interaction with the actors, but needs to be carefully adjusted based on the real-life experimentation.

3.3 The Environment

The classification of an environment makes sense when we begin to describe the overall performative space in which the actors are performing. Essentially the task is to make the actors part of the environment in a way that they perceive e modular robot as supportive for the current tasks. Here interaction becomes essential because the occupants take prime role in configuring the space through a deliberative and variable response to each in a series of exchanges [11](p. 61) [17](p. 20).

The main feature of the environment is thus a performative space acting as a platform for a series of variations and uses, which intelligently adapts to the specific behaviours of the actors. The interaction with the modular robotics happens as a bi-directional communication, where each element supports the purpose of the overall behaviour of the system. The modular robot creates the morphological boundaries of the space, but needs to be supported by elements like audio, light, material textures etc. in order to sufficiently afford the intended behaviours [18, 19]. The environment can then be classified as the overall ambient ecology in which the stated behaviours are supported.
4 Applying ModWall to Pig Stables

In applying the ModWall concept to solve the challenge presented in the introduction we have to consider the actors, the modular robot and the environment as outlined in the previous section. The actors are naturally the slaughter pigs, the modular robot some kinematic/dynamic realisation of a modular robot able to provide a morphological boundary concept comprising stalls and pathways, and the environment a stable system comprising the necessary infrastructure in terms of outer walls, sensors, lighting, audio and the likes.

This section, though dedicated to all three system components, will focus mainly on the modular robot as it is the larger contribution of this work. The other two components will only be handled briefly to give the reader an idea of how the system might function as a whole in a given real-world implementation. The resulting concept can be seen from Figure 5 and Figure 6.

4.1 The Slaughter Pigs

Studies with pigs in the 1990’s considered pigs as some of the more intelligent and curious of animals; they indicate complex social behaviours, a good sense of direction and quickly learn from each other. This implies that movement of pigs in an appropriate manner with least stress requires a much orchestrated process combining the ambient effects of the building environment with the more specific interaction with a modular robot.

In this study the pigs are as shown in Figure 1 entering a weighing system at the beginning of relocation, making it possible to adjust the specific location in the stable depending on the most appropriate sales-price. Each parameter of the space is optimised in relation to welfare issues and adjusts individually according to the specific pig by initially lighting up the end-space. An audio system follows the pig gradually through the space and the corridors of the modular robot open up as to indicate a progress in movement and stimulate curiosity of the individual pig. The interior materials of the space are designed with a semi-transparent and light expression and a soft floor material to indicate both safety and a comfortable walking zone for temporary instalment of the pigs.

To integrate the individual behaviours of pigs in relationship with the building elements requires a specific design scenario combining robotics with building design. This task of achieving the full functionality of the modular robot within a complex environment is initially approached through activity-centred design [21](p. 33) sharing some resemblances to elements of HRI and HCI. Essentially it is part of an interaction design scheme, but instead of looking at very specific goals from a user or system perspective when interacting with the individual wall element, the activity-centred design approach focus on the clustering of actions and decisions that are done for the purpose of fulfilling the overall activity, e.g. moving pigs through a dedicated space. Activity-centred design is especially applicable when understanding the complex behaviours that need to align between several actors, in order to fulfil the overall functionality of the system, and is much tied to actual physical mock-ups and experimentation with different scenarios.

4.2 The Modular Robot

In the following subsections a simple modular robot capable of producing a morphological boundary concept in pig stables will be presented. First, a presentation of the robot’s modules will be given, leading to a presentation of some kinematical aspects of the resulting robot and finally a presentation of some issues regarding the robot’s configuration and re-configuration.

4.2.1 Modules

To solve the task at hand we will focus our efforts on devising a modular robot able to construct closed stalls and pathways to mimic the traditional static layout of pig stables. We can accomplish this by applying basic module types where the actuation is a single vertical turn-able infra-structural column with either 1-DOF or 2-DOF actuation and where the actuated elements are wall-pieces each hinged to a separate DOF. Such wall elements can potentially be of many shapes and materials optimised in accordance with given requirements but we choose to consider only two types of rectangular wall elements: One with length l and its axis of rotation coinciding with its geometrical centre, and one with length l/2 and its axis of rotation through one of its endpoints. We denote these types of wall elements as simple-symmetrical and simple-asymmetrical and use \( \theta \) to denote their current angular position. The simple-symmetrical elements are always hinged to a 1-DOF column but the simple-asymmetrical elements may be either hinged separately to a 1-DOF column or in pairs to a 2-DOF column.

As we apply modules with an infra-structural column we only consider a robot where the modules are arranged in some 2D ground formation. Here the simple-symmetrical modules can in simple plan view, at \( \theta = 0 \) radians, graphically be represented as a dot (the column) with an intersecting line (the wall element): ●—●

This representation is also equivalent to a simple-asymmetrical 2-DOF module with one wall at \( \theta = 0 \) radians and one at \( \theta = \pi \) radians, where the 1-DOF version would simply look like: —●
4.2.2 Kinematics

To gain a better understanding of a modular robot comprising these basic module types we will take a look at its kinematics. For a ModWall modular robot using the previously described basic module types we define its module configuration to be the column vector, \( q \in \mathbb{R}^n \), where \( n \) is the total number of DOFs in the robot and the \( k \)-th element of \( q \), \( q_k = \theta_k \), is the angular position of the \( k \)-th actuator according to some numbering scheme. As the robot can display infinitely many distinct boundary layouts we initially limit this number by only regarding the static configurations, that is, where all wall elements are at a standstill and furthermore constrain these configurations such that only \( q_k \in \{ \frac{\pi}{2} \cdot x \mid x \in \mathbb{N}_0 \} \) is valid. By ordering the modules in a static mono-spaced lattice formation with each row shifted by \( l/2 \), we now have the possibility of creating layouts with closed spaces and pathways with no possibility of wall collisions. Figure 3 shows four example boundary layouts produced using a robot comprising 17 simple-symmetrical modules. More elaborate examples using 96 simple-asymmetrical 2-DOF modules can be seen in Figure 4.

![Figure 3: Four example configurations showing the versatility of a layout of 17 modules. The first example shows six closed spaces. The second, two separate open-ended paths. The third, a closed-circuit labyrinth-like pathway and the fourth, two separate tracks with entry/exit points pair-wise together.](image)

![Figure 4: Four different configurations of a ModWall robot comprising 96 2-DOF infra-structural columns with simple-asymmetrical elements. As can be seen the morphological range is large ranging from closed areas of various kinds, random labyrinth-like structures to simple pathways. Note that the last configuration allows \( \theta = \pi/2 \) radians.](image)

As can be observed, redundancy exists when symmetrical wall elements are used as \( \theta_k = \theta_k + x \cdot \pi \) for \( x \in \mathbb{N} \) and produces the exact same boundary configuration. We therefore distinguish between module configuration and boundary configuration of a modular robot, where the former relates to the individual actuation elements and the latter to the system-level structure formed by the entire set of wall elements. We define the boundary configuration of a ModWall modular robot comprised of basic module types as the column vector, \( b \in \mathbb{R}^m \), where \( m \) is the total number of simple-asymmetrical wall elements needed to realise the robot. That means that all 1-DOF simple-symmetrical elements are represented as two elements in the boundary configuration which in turn means that \( \dim(b) \geq \dim(q) \). The \( k \)-th element of \( b \), \( b_k = \theta_k \), is the angular position of the \( k \)-th simple-asymmetrical element equivalent ordered according to some numbering scheme and such that the angular positions of each column are in ascending order. This ordering ensures that redundancy is eliminated.

4.2.3 Configuration and Re-configuration

When specifying a desired boundary layout for the modular robot utilising the boundary configuration is the natural choice as it is only concerned with the actual static stable structure not with the actual angles of the individual DOFs. In this study the specification of these desired configurations are done in part manually and in part based on the sensor input from the environment indicating, for instance,
where each pigs is located. The manual entries are done prior to the operation of the system and gives an overall plan for solving the task. The sensor information may on the other hand modify the current boundary configuration locally or actually trigger a system wide re-configuration.

The task of dynamic re-configuration of the modular robot is equivalent to finding and executing the intermediate time dependent configurations between desired static boundary layouts – a process also commonly known as motion planning or re-configuration planning. This task is not trivial as the design of the static boundary layouts are specified using boundary configurations and not module configurations which are needed to conduct the actual motion of the walls. This introduces an obvious challenge: The transformation of a module configuration to its resulting boundary configuration is always straightforward as only one solution exists, but the opposite is naturally not the case – parallels to the problems of finding closed-form solutions to the inverse-kinematics problem of robotic manipulators [20] are evident. Various methods for handling the dynamic reconfiguration problem for modular robots do, however, exist but is out of scope of this paper. It is nevertheless an essential area to address in order to obtain an actual working system and it will therefore be handled in our future work. For now we just assume that some sound means of transition between configurations exist.

4.3 The Stable System

The overall stable system exists in harmony with the full performative building where each parameter included in intelligent buildings installations like ventilation, light, audio, wall elements etc. supports the actual activities in the stable and the intended behaviours of the pigs. Essentially all parameters in the building assist in providing the most optimal affordances adjusted to the user experience and performance scenario.

Besides the modular robots, the stable environment consists of a dynamic lighting system making it possible to illuminate entrance and exist of the space as well as the individual zones in the morphological boundary concept. With this lighting concept colours can create different emotional feedbacks as well as stimulate either flow (white-blue and contrast) or steadiness (warm red empha-sizing colours). A dynamic audio system can relocate sound in similar groups to stimulate how different areas of the space feel more or less interesting and comfortable at the same time as the general materiality of the space is soft, light and flexible. The overall performative system works together with the weighing and tracking system which positions each pig in the space and makes it possible to direct a unique performance criteria for each individual behaviour.

When the pigs move through the ModWall system, they are encased in a refined and sensible interaction with the ModWall system. Initially the robot interaction is based on knowledge about perception and distant measurements of boundary objects, and to which level and speed the ModWall system can move in relation to the distance to the individual pig. This involves very detailed studies on how much the wall will move when a pig is approaching in order to support the most delicate and safe relocation scheme. At the same time careful studies are being made of wall materials, textures and the speed of movement in relation to the interaction scheme. Over time a higher level learning system will integrate more factual knowledge about pig interaction and flock behaviours. Here experimentation is still being processed regarding how the ModWall can support the flow of animals through the space on the premise of understanding movement and orientation in space.
The further development and maturing of the ModWall concept will be conducted in close cooperation with the other StaldTek partners where the next step is to construct a software simulator together with a table-top sized version of the modular robot. This setup will allow us to gain further experience in movement scenarios and control strategies as well as allow us to conduct specific interaction studies on a small scale. In this process we will have special emphasis on additional dialogue with researchers within animal behaviour and intelligence, as well as involve the potential end-users regarding strategy and barriers for implementation – e.g. user scenarios, maintenance issues and cost-benefit. This will further lead to the development of a full performance study with detailed interior of the buildings including lighting design, materials, audio system etc.

5 Conclusion

In this paper we have presented ModWall, a morphological boundary concept based on a modular robot comprised of simple and interactive wall elements. We have shown how this concept can be integrated with building design to orchestrate the movement of pigs in a delicate way and with a focus on both animal and staff welfare. Through an example case we have further shown how it potentially can support the process of relocation and separation of pigs in new efficient pig production systems.

Through this we have also demonstrated the flexibility and versatility of the concept by showing versions of the modular robot ranging from pure homogenous types (all wall elements are identical) to heterogenous types (the wall elements may be different). This flexibility offers a perspective towards fully automated performative production systems not only within animal production but in many places where the reconfiguration of boundaries could be useful – perhaps as queue control at airport security checkpoints.

References


