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Research Paper

Path planning for the autonomous collection of eggs on floors

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A problem in loose housing systems for laying hens is the laying of eggs on the floor; these eggs need manual collection. This job is heavy and time-consuming and automated collection is desired. For collection using a robot, a collection path is required. A novel path planning algorithm is introduced for non-uniform repetitive area coverage (NURAC) paths and evaluated based on information about floor egg distribution probability. Firstly, a spatial map was developed that describes the potential for floor eggs at each location in a poultry house. Next, paths for floor egg collection are planned with a dynamic programming approach that covers the house floor area and frequently revisits locations with a high potential on floor eggs. These paths are compared with the paths used for floor egg collection by a farmer and evaluated with help of a simulated set of floor eggs. With respect to the average time eggs are present on the floor, paths planned for a robot are compared to two collection rounds of a farmer. With respect to the structure of the path and the number of visits to locations with a high potential, the robot paths outperform the farmer. Although optimality of the path is not guaranteed, the presented results are promising for the use of a robot to collect floor eggs, and will result in a reduction of the demand for manual labour. Extending the floor egg model with feedback information could further improve the results.

1. Introduction

1.1. Floor eggs

Based on the increasing concerns of the public about the welfare of production animals, the EC issued a ban on egg production in traditional battery cages by 2012 (European Union, 1999). Since the 1980's, this led to a search for alternative systems, categorised as enriched cages or colony systems and loose housing systems. The basics of the latter type are centuries old but to comply with modern farming practice improvements in scale and productivity were necessary. As a result, the aviary system was developed (see Blokhuis & Metz, 1995; Sandilands & Hocking, 2012) which increased productivity while maintaining freedom of behaviour for the animal.

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Nomenclature

μ	Mean
a	Instance of length index
b	Instance of width index
C_k	Contribution at stage k
c_1–c_4	Constants controlling the incentive function
Egg time	Time an egg is present on the floor, h
f	Factor controlling the yield increase
I	Number of cells in length of the house
i	Cell index in length direction
J	Number of cells in width of the house
j	Cell index in width direction
k	Index of cell transition or stage
L	Total set of locations
$L_{i,j}$	Location i,j, with $i = 1{:}I$, $j = 1{:}J$
N	Number of cell transitions
O	Optimisation criterion
$P_{i,j}$	Floor egg potential at location i,j
$P_{i(k),j(k)}$	Floor egg potential at location i,j at stage k
$R_{i,j}$	Incentive at location i,j
$R_{i(k),j(k)}$	Incentive at location i,j at stage k
T_k	State transition at stage k
t	Time, h
$t_{collection}$	Time of collection of an egg, h
t_{lay}	Time of lay of an egg, h
U	Set of possible transitions or decisions
u_k	Decision at stage k
V_k	Value function at stage k
X	Width direction of the house
x_k	State at stage k
Y	Length direction of the house
$Y_{i,j}$	Yield at location i,j
$Y_{i(k),j(k)}$	Yield at location i,j at stage k
Y_{max}	Maximum yield
σ	Variance

In these systems hens are trained and expected to lay their eggs in the nests; However, a significant portion can be found at other places such as elevated tiers and the floor (either litter or slatted floors) and these eggs are called ‘mislaid eggs’.

Laying of eggs outside the nests is induced by factors such as the inability of the hen to reach the nest, unfamiliarity with laying (especially at a younger age), conceptual mismatch between the properties of the nest and the expectation of the hen and presence of other eggs outside the nest (Appleby, 1984; Zupan, Kruschwitz, Buchwalder, Huber-Eichter, & Stuhec, 2008). Eggs laid in the litter on the floor are considered to be a problem in poultry farming. They have a lower quality due to contamination by the litter and they induce additional floor laying. Thus frequent collection of floor eggs is required (Abrahamsson & Tauson, 1998; Appleby, 1984; Emous & Fiks-van Niekerk, 2003; Emous, Reuvekamp, & Fiks-van Niekerk, 2001). Research has been done on measures to reduce the laying of floor eggs. This has led to specific adaptations of the housing systems and a series of management and control measures used by farmers. None of them has proven to be completely successful (Abrahamsson & Tauson, 1998; Appleby, 1984; Cooper & Appleby, 1996a, 1996b; Emous & Fiks-van Niekerk, 2003; Gunnarsson, Keeling, & Svedberg, 1999; Lundberg & Keeling, 1999; Tauson, 2005; Zupan et al., 2008). One of the key control measures taken is the frequent manual collection of floor eggs. This is a physically demanding job under harsh environmental conditions and it can take up to 37% of the work time of the farmer (Blokhuis & Metz, 1995; Drost & van der Drift, 1993; van den Top, Akkermans, & Oude Vrielink, 1994).

1.2. Egg collection

To ease this collection task, for instance, a gripper stick, an automated collection system with a rake (Fiks-van Niekerk, Reuvekamp, van Emous, & Ruis, 2003) and the Chicken Trolley (“Chicken Trolley,” 2010) have been proposed. However, despite the enormous progress already made, it is expected that the problem of floor laying will remain with current systems, as a result of variations between flocks and the specific preferences of the hens with respect to their nesting places.

Another alternative is to use an autonomous multi-functional robot platform for the collection of floor eggs. It could also be used for the monitoring of indoor climate, identifying dead hens, monitoring animal behaviour and welfare and perform other tasks thereby alleviating the work of the farmer, without the need for a fixed installation in the poultry house. This idea builds on a robotic platform that was constructed for the Field Robot Event competition of 2007 (Proceedings 5th Field Robot Event, 2007). In the free-style task of that competition, an autonomous robot with a collection device demonstrated the collection of floor eggs (Kool, Vroegindeweij, Wollerich, & van der Zwaag, 2007). The basic idea was well received in agricultural practice in The Netherlands (Bijleveld, 2007).

As a result a research project started in 2011 at Wageningen University focussing on the development of such an autonomous multi-functional platform. To ensure safe and correct functioning of such a platform, essentially, the following functions need to be implemented (Bechar, 2010), 1) mobility, steering and control, 2) sensing, 3) path planning and navigation, 4) manipulators and functional devices to deal with products, and 5) intelligence and autonomy.

1.3. Path planning methods

This paper addresses the path planning for such a platform focussing on floor egg collection. The path planning algorithm had to take into account that floor eggs are non-uniformly distributed with respect to space (the location in the aviary house) and time (the moment the eggs are laid). Given these characteristics, key requirements for the path planner were: 1) the time that eggs lie on the floor should be minimised to prevent loss of quality; 2) the robot should cover the whole aviary house in 24 h; 3) the robot should be able to exploit the non-uniform distribution of floor eggs in the poultry house; 4) during the ovipositioning period the robot should frequently (re-)visit locations with a higher probability on floor eggs and pay less visits to locations where the potential for floor eggs is lower.

The second requirement suggests a solution in the direction of coverage path planning (Choset, 2001; Zelinsky, Jarvis, Byrne, & Yuta, 1993). However, such algorithms commonly focus on a uniform coverage of an area and tend to limit as much as possible revisits to a location. The current problem is more related to the field of (security) sweeping. The latter, also known as patrolling, is defined by (Elmaliach, Agmon, & Kaminka, 2009) as: "travelling around an area to supervise it". With this approach, locations can be visited multiple times, but in general, this approach attempts to have a uniform visiting frequency for all locations. This can for example be done by planning a Hamiltonian cycle along all locations, and repeatedly covering this path, either by a single or multiple robots (Elmaliach et al., 2009).

For a quite similar kind of problem, autonomous floor cleaning and trash collection in a large building, Ahmadi and Stone (2005) proposed a method that accounted for a non-uniform distribution and, consequently, a frequent revisit to regions of interest. Their approach relied on a world model which is based on on-line event registration and learning, followed by a greedy search algorithm for generation of the path. It is worth noting that, to the best of our knowledge, in the domain of deliberative robot path planning (LaValle, 2006), the algorithm of Ahmadi and Stone (2005) is the only example of a path planning approach explicitly dealing with frequent non-uniform revisits of regions of interest. In the current paper, we follow a more or less similar approach but for floor egg collection. Main differences are that here path planning will be based on a map containing the potential for floor eggs for each location in the aviary house. Additionally, path planning will be use a dynamic programming (DP) approach so as to assure close to optimal behaviour and enable global search.

1.4. *Objective and paper outline*

Our objective is to automate the collection of floor eggs with a robot. Here, a novel path planning algorithm is presented for non-uniform repetitive area coverage (NURAC) paths. However, firstly we present the a priori knowledge for the algorithm, including a model describing the potential on floor eggs, then, we introduce the path planning algorithm. In a model case study, the path generated by the newly developed algorithm is compared with manual floor egg collection by the farmer. The paths will be evaluated in qualitative terms by looking at the structure of the path. It will also be evaluated in quantitative terms by the average time eggs spent on the floor and the number of visits to each location.

2. A priori knowledge as input for the path planner

In this section, the approach of the NURAC path planning system together with the information that is used as a priori knowledge for the path planner is presented. This contains a description of the reference aviary house that was used as starting point and a short description of the floor egg model with underlying literature that was used.

2.1. *Coverage path planning for automatic floor egg collection*

For coverage path planning to collect floor eggs autonomously the procedure as shown in Fig. 2 is envisioned. Based on a priori knowledge of floor egg laying and a map with information on the housing and elevated tiers, a map is constructed which contains the location specific potential on the presence of floor eggs. This potential is related to the number of floor eggs that can be expected at each location. Next, a collection path for the robot is planned. Eggs in the aviary house are collected by following this path. During this process, information is collected about actual locations of floor eggs found. Based on this information, the floor egg potential map can be updated for the collection round on the following day, increasing the potential at locations where floor eggs were found and lowering the potential at locations where no floor eggs were found, as indicated by the feedback loop in Fig. 2. This updated map is then available for (re-) planning of the coverage path for next day. As a result, the

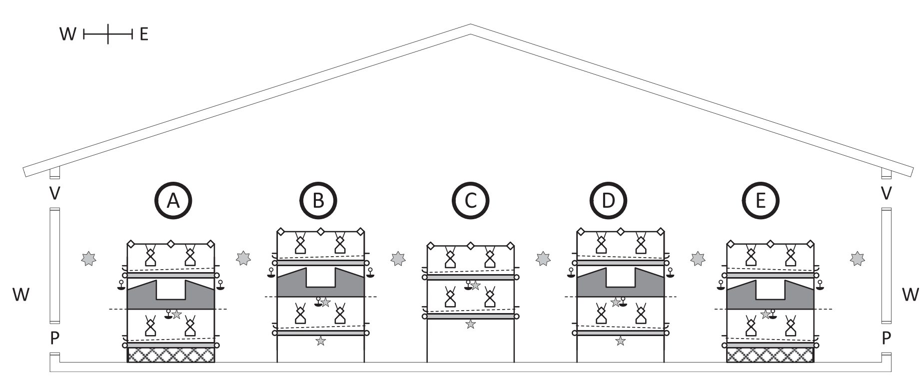

Fig. 1 – Cross-section of the reference poultry house (along X-direction). On both sides of the housing a Winter Garden (W) was present, accessible via pop holes (P). In the aviary house, rows with elevated tiers (indicated A to E) with feeding lines, drinkers, perches and laying nests were present. The whole floor was covered with litter for scratching and dust bathing, except for the rows on the outside (A and E), below which the floor area was not accessible. The free height below the elevated tiers was 0.9 m for the middle row C, and 0.4 m for rows B and D.

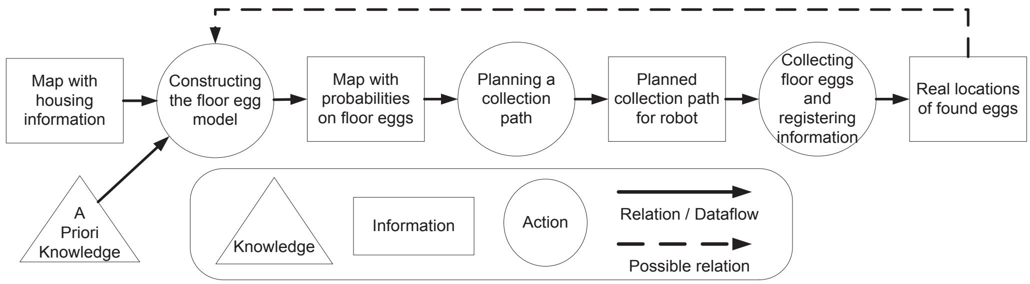

Fig. 2 – General model of the path planning approach.

distribution is initially the same for all sections in the house, but distributions will start to diverge once the first eggs have been found.

In this paper, the focus is on a part of this procedure, namely the generation of a map with the potential on floor eggs as well as the generation of a collection path. The performance of the resulting path is evaluated in a simulation setting and referenced to the collection behaviour and performance of a farmer.

2.2. *The commercial aviary house used in this case study*

To have a reference situation for our model and to enable comparison of the results with practical experiences, research was based on an aviary house operated by the commercial farm 'Het Anker B.V.' at Opheusden, The Netherlands. The house accommodated 36,000 laying hens and was equipped with 5 rows of the Farmer Automatic Aviary (model year 2003, Farmer Automatic GmbH & Co. KG, Germany). A cross-section of the house is shown in Fig. 1. On the four outer rows (A, B, D and E), Van Gent group laying nests (Van Gent International BV, The Netherlands) were provided. The front of the house was opposite to the wall where the ventilation fans were placed. The housing was longitudinally divided into six sections by mesh wire fences. The Winter Garden was not considered in this research as hens only got access to the Winter Garden after laying. The width direction (X) is defined along the cross section of the house, while length direction (Y) is defined along the aviary rows.

2.3. *Generation of a floor egg potential map*

Since experimental data on floor egg distribution were not yet available, a map was constructed containing a location specific potential on the presence of floor eggs. The resolution of this map was 0.1 by 0.1 m, and such an area was called a location. This location is expected to contain maximally 1 egg at a time. For each location on the map, a potential (P) between 0 (never a floor egg) and 1 (every day a floor egg) was calculated. The map was generated with MATLAB® 2012a. Appearance of floor eggs in space and time is generally influenced by the following aspects: 1) hens tend to have a preference for particular locations in the house when laying floor eggs, 2) egg laying and thus floor egg appearance during the day is correlated with the natural laying behaviour of hens on a diurnal basis, 3) the overall number of eggs and thus also the number of floor eggs produced during a day depends on the time in the production cycle, 4) laying behaviour depends on the particular type of hen. Hereafter, the first three aspects will be described in more detail. The effects related to a particular type of hen (originating from breed, strain and flock), will not be considered in this research.

2.3.1. *Location specific aspects*

Literature indicates that hens tend to lay eggs near the front wall and to a lesser extent near the rear wall of the house (Emous & Fiks-van Niekerk, 2003; Niekerk & Reuvekamp, 1997). It is also indicated that hens prefer enclosed locations, like close to walls and corners and below and near construction elements (Appleby, 1984; Lundberg & Keeling, 1999). Darker locations also show a higher probability on floor eggs (Ellen, van Emous, & Kruit, 2007).

Floor egg potential, as a function of distance to a wall or fence, was described with an exponential decay function. For each of the four corners in a compartment these functions were combined, to form the potential map for a single compartment. A higher weight was given to the corners at the front side of the compartment. Also, a correction was made for the walkways between the aviary system and the border of the housing. It is known from practice that they contain less floor eggs, probably due to a lower animal density, draught from the pop holes to the winter garden and the fact that these areas are used by the hens as a transit from the house to the winter garden. The floor egg potential was modified in two steps. Firstly, the potential was increased depending on the height of construction elements above the floor. In case this height was zero, the potential was set to zero. Construction elements close to the floor, but accessible for the hens, led to a higher increase in potential than construction elements more elevated over the floor. Secondly, the potential was increased for locations close to construction elements or walls, with an increase that was inversely proportional to the distance.

Figure 3 shows the resulting map with the location specific potential on floor eggs in the house, in which blue indicates a low potential and dark red indicates a high potential. This represents an initial situation, and can be updated based on the locations of the collected floor eggs, as stated earlier. This map was partially validated with floor egg data from practice and the results showed a qualitative agreement (Vroegindeweij, Van Henten, Van Willigenburg, & Groot Koerkamp, 2013). Also, the map was shown to two farmers and they confirmed

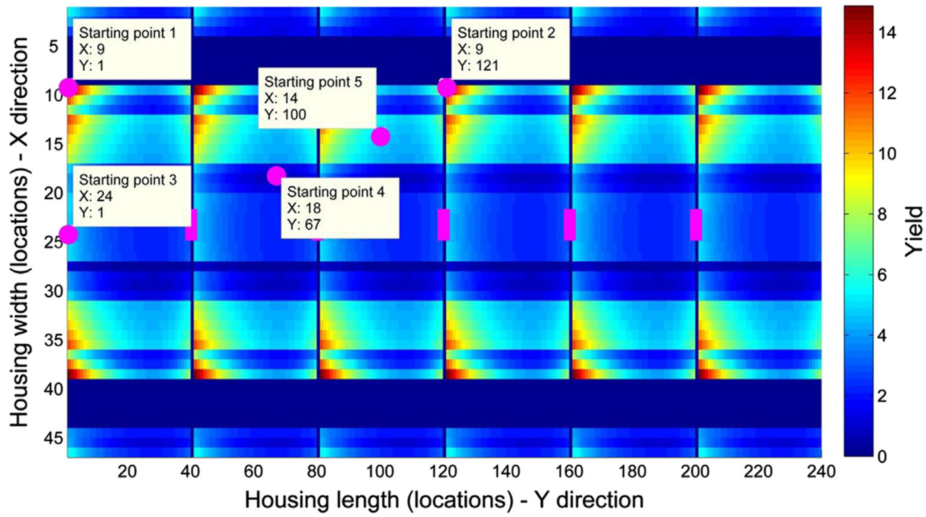

Fig. 3 – Initial yield map for the path planning which equals the summed floor egg potential. Blue indicates a low potential and dark red indicates a high potential. The horizontal dark blue lines refer to rows A and E in Fig. 1, indicating areas that cannot be accessed by the robot or the hens. Purple dots indicate the starting points for the robot paths with their specific coordinates. The purple bars represent the robot passage ways between the sections.

the general trends in the location specific potential distribution of floor eggs based on their practical experience. Therefore, it was considered to be a good starting point for generation and evaluation of robot paths. For the path planning, the resolution of the map was changed from a single-resolution grid of 0.1 by 0.1 m into a multi-resolution grid of 0.4 by 0.4 m in open areas, and smaller grid sizes to accommodate the presence of interior elements. This was done by summing the potential of the single-resolution cells which were combined into one cell in the multi-resolution grid, so that the cells in the multi-resolution grid could take values between 0 and 16. The multi-resolution grid is only used to adapt the map to the presence of interior elements, in that it remains possible to preserve specific features in the potential yield map. For the path planning algorithm, this is of no relevance, as all cells are treated equally irrespective of their size.

2.3.2. *Diurnal aspects*

Joly and Alleno (2001) studied the diurnal egg laying pattern. They found that egg laying in time followed a logistic pattern that was closely correlated to the 'lights out' moment the previous day. Based on these data, a logistic function was fitted that matched the laying behaviour of the flocks at the example farm studied in this research. The resulting curve is shown in Fig. 4.

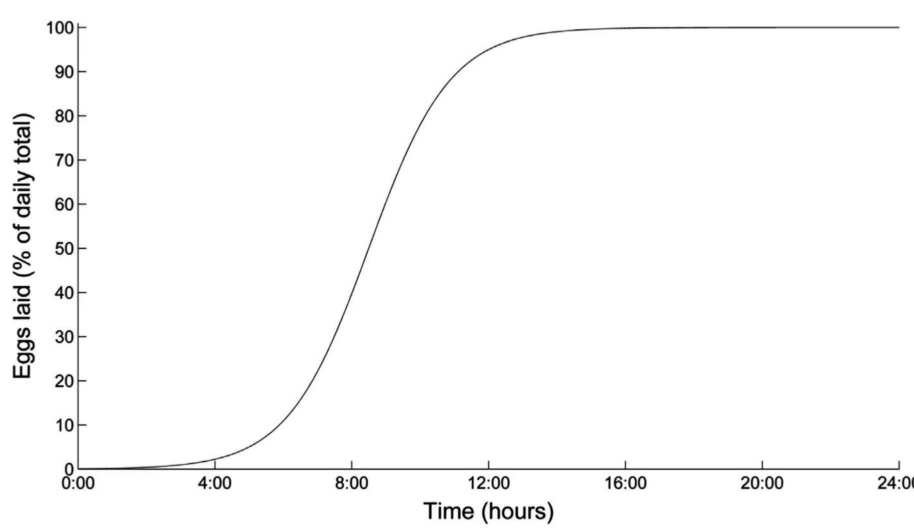

Fig. 4 – Cumulative (floor) egg production over a single day, based on the total production of eggs within a single day (Joly & Alleno, 2001). Lighting was switched off around 22:00 h the previous day.

2.3.3. Seasonal aspects

The number of floor eggs laid during a production cycle depends on: 1) the daily production level, and 2) the fraction of eggs laid on the floor. Egg production data were obtained from ISA Poultry (2008) for the breeds Isa Brown, Hisex Brown and Bovans Brown. These data were averaged on a daily basis. The fraction of eggs laid on the floor was based on data of Emous et al. (2001, 2004). These fractions are also known to vary in time. Usually, the number of eggs laid outside the nest is high in the beginning of the production cycle. Proper management and hen learning usually results in a decreasing number of eggs laid outside the nest. Additionally, during the first part of the production cycle, mislaid eggs are usually found on the 'system tiers'. Later on, more eggs are found on the floor. As there is day to day variation in the number of eggs laid by flock, a random component is added from a normal distribution with $\mu = 0$ eggs and $\sigma = 10$ eggs, based on observations in the reference poultry house. Figure 5 shows a realisation of a time series of the daily number of floor eggs produced by a flock of 36,000 hens during a single production cycle, as used in this research.

3. Coverage path planning with non-uniform frequency of revisits to hot-spots

The solution of the coverage path planning problem is based on an approximate cell decomposition of the aviary house (Choset, 2001) and an algorithmic approach closely related to dynamic programming. The cell decomposition yields a set of locations L. In this example, each location $L_{i,j}$ is indicated by the indices $i = 1,2,\ldots,I$ and $j = 1,2,\ldots,J$ that are related to the location of the cell along the width and the length of the aviary house, given as X and Y respectively in Fig. 3. For the path planning, the aviary house was decomposed into cells of 0.4×0.4 m resulting in around 11,000 cells. A robot having an assumed speed of 0.2 m s^{-1} will be able to traverse such a cell in 2 s. As hens will start laying floor eggs some 7 to 10 h after lights-out, the robot will start sweeping the aviary house around 6:00 in the morning. It is assumed that approximately 13.5 h of operation will be sufficient to remove all floor eggs. Given these preliminaries, the robot has to make about 24,000 cell transitions during its operation period on a day. Then the objective of the coverage path planning is to find a path through the aviary house consisting of $N = 24{,}000$ cell transitions that satisfies the following requirements:

1. It should minimise the time eggs lie on the floor,
2. It should completely cover the whole aviary house, i.e. all 11,000 cells,
3. Repeated visits are allowed, preferably to locations with a high potential on floor eggs,
4. It should stimulate visits to locations with a high potential on floor eggs in the beginning of the laying period and, vice-versa, it should stimulate visits to areas with lower potential later on the day.

Objective one is hard to accommodate since it is unknown when exactly an egg has been laid and therefore, under practical conditions, the time that eggs have spent on the floor, the so-called egg time, cannot be assessed. In a simulation, this egg time can be assessed, but this is of limited use as the algorithm ultimately has to work under practical conditions as well. Therefore, it does not make sense to use this objective as objective function for the path planning procedure. As an alternative, it was decided to maximise the yield of floor eggs collected per day while traversing the aviary house. As indicated in section 2.3, the distribution of floor eggs, and thus the yield per cell, is related to the potential for floor eggs in each cell, the time on the day and the day within the production cycle. Thus the objective was defined as to find a path such that this yield

$$O = \sum_{k=1}^{N} Y_{i(k),j(k)} \tag{1}$$

is maximised. Here indices $i(k)$, $j(k)$ specify the location visited at instant k, N is the total number of visited locations. $Y_{i,j}$ is the yield at location i,j given by:

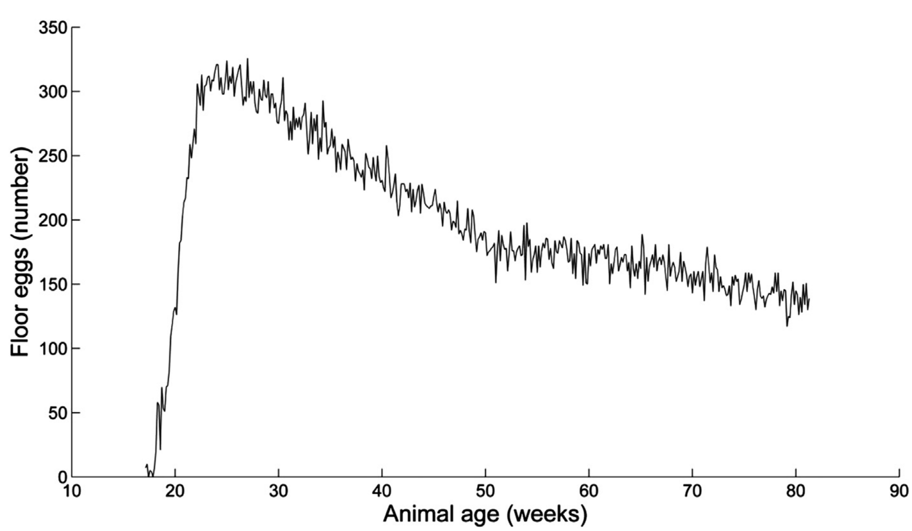

Fig. 5 – Simulated daily number of floor eggs, produced during a single production cycle by a flock of 36,000 hens.

$$Y_{i,j} = P_{i,j} \tag{2}$$

with $P_{i,j}$ the potential on floor eggs at location $L_{i,j}$ as defined in the floor egg potential map. $P_{i,j}$ takes values in the range [0,16], which relate to a range of 0–16 eggs per cell. Cells containing a wall, fence or interior elements that cannot be accessed by laying hens and robots have a value of the potential $P_{i,j} = -\infty$.

It can be shown that a dynamic programming solution maximising the objective of Eq. (1) given the yield function of Eq. (2) will result in a shortest path solution to the location with the highest potential on floor eggs reachable within the available number of cell transitions N. Then, oscillatory motions will occur between this location and the neighbour with the next highest yield. To make sure that the robot will cover the whole aviary house, including locations with lower potential on floor eggs, the yield function was modified to account for the effect of egg collection according to second requirement stated above. When the robot has visited a location, it has gathered all the eggs in this location which means that, immediately after the visit, the yield should be equal to zero. Then, after the visit, the yield to be acquired in that location was considered to grow again due to the fact that hens will continue laying eggs also at the locations already visited by the robot. For locations that have not yet been visited, the yield function of Eq. (2) was used. However, for locations visited by the robot a modified yield function was used. In that case the yield was defined as

$$Y_{i(k),j(k)} = \left(P_{i,j}\right)^2 \cdot \frac{\Delta k}{N} \cdot f \tag{3}$$

with $P_{i,j}$ the potential on floor eggs at location $L_{i,j}$ as defined in the floor egg potential map, Δk is the number of cell transitions between the current visit and the previous visit and f is a factor. In this research a value $f = 0.1$ was used which ensured that for locations with a high potential after 0.5 N cell transitions the yield was equal to the original yield. The modified yield function guaranteed that for locations with a high potential on floor eggs, the yield will grow faster than for locations with a lower potential on floor eggs. This represents the situation as encountered in practice, and complies with the third requirement stated above.

The fourth requirement was accommodated by introducing an incentive function that takes high values for cells with a high yield during the beginning of the search period and that gives an increasing reward for cells with a lower yield during the final stretch of the search period. For this purpose the objective function of Eq. (1) was extended to

$$O = \sum_{k=1}^{N} Y_{i(k),j(k)} \cdot \left(R_{i(k),j(k)}\right)^2 \tag{4}$$

in which $R_{i(k),j(k)}$ is the incentive function defined as

$$R_{i(k),j(k)} = \exp^{-1\cdot\left(((N-k)/N)/c_1 + \left(Y_{i(k),j(k)}/Y_{\max}\right)/c_2\right)} + \exp^{-1\cdot\left((k/N)/c_3 + \left(\left(Y_{\max} - Y_{i(k),j(k)}\right)/Y_{\max}\right)/c_4\right)} \tag{5}$$

in which $Y_{\max}$ is the maximum value of $Y_{i,j} = P_{i,j}$ taken over all i and j, and c_1 to c_4 are empirically determined parameters having values $c_1 = 1.3$, $c_2 = 0.9$, $c_3 = 1.5$ and $c_4 = 1.5$. The first exponential promotes a high potential at the beginning of the path, while the second exponential promotes a lower potential towards the end of the path. Each exponential contains a component for time and one for reward.

With the objective function defined as above, the path planning problem was solved using a dynamic programming (DP) approach (Bertsekas, 1995). In DP, optimisation problems are usually defined in terms of the stage k, the state x_k, a decision or control variable u_k, a state transition $T_k(x_k,u_k)$, an objective function V_k and the contribution $C_k(x_k,u_k)$ of a state transition to the objective function.

In the current problem the state of the system x_k represents the location of the robot $L_{i,j}$ in the environment at stage k. A motion of the robot, i.e. a change of the state from x_k to x_{k+1}, constitutes a transition from a cell to one of its neighbours. This transition is considered to be the decision variable $u_k \in U$. For every x_k the set of possible transitions U consists of $\{(1,1),(1,0),(1,-1),(0,-1),(-1,-1),(-1,0),(-1,1),(0,1)\}$. Then, the state transition function is $T_k(x_k,u_k) = u_k$ and the transition is $x_{k+1} = x_k + u_k$. For example if $x_k = L_{i(k),j(k)} = 5,2$ and $u_k = -1,1$ then $x_{k+1} = L_{i(k+1),j(k+1)} = 4,3$. The contribution to the objective function of a decision u_k yielding a transition from state x_k to x_{k+1} is $C_k = C_k(x_k,u_k) = Y_{i(k),j(k)} \cdot (R_{i(k),j(k)})^2$ with $Y_{i(k),j(k)}$ dependent on whether or not a cell has been previously visited or not as defined in Eqs. (2) and (3). The value function is defined as

$$V_k = \max_{(u_k,\ldots,u_N)} \sum_{k}^{N} C_k(x_k, u_k) \tag{6}$$

It represents the optimal cost of travelling from the state x_k to the final state x_N. Then $V_0(x_0)$ indicates the optimal value of the objective function while travelling from state x_0 to state x_N. Furthermore, $V_N(x_N) = 0$, because the robot stops at instance N and therefore no additional reward is to be obtained.

When the system satisfies the so-called Markovian property (future and past states are independent when the current state is known), the principle of optimality indicates that "*whatever the initial state and decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision*" (Bellman, 1957). The Markovian property requires that current and future decisions cannot have any effect on past system behaviour (Larson & Casti, 1978). Then, a recursive equation for the value function can be derived:

$$\begin{aligned} V_k(x_k) &= \max_{(u_k,\ldots,u_N)} \left[C_k(x_k,u_k) + V_{k+1}(x_{k+1})\right] \\ &= \max_{(u_k,\ldots,u_N)} \left[C_k(x_k,u_k) + V_{k+1}(x_k + u_k)\right] \end{aligned} \tag{7}$$

This equation is usually solved in reverse order from $k = N$ to $k = 1$.

The current problem does not satisfy the Markovian property (decisions from the past *do* effect future costs in our problem) and therefore DP will not provide an optimal solution. The reason lies in the fact that the expected *future* yield $Y_{i,j} = P_{i,j}$ *changes* depending on *past* visits to $L_{i,j}$. The following example illustrates why DP does not provide an optimal solution. It also describes the way we try to remedy this problem.

DP recursively computes the solution backward in time from $k = N$ to $k = 1$. Assuming that at $k = 20$ the optimal decision is to let the robot visit location $L_{i(20),j(20)} = L_{a,b}$. Then during further computation of the solution, backward in time, it might happen that at $k = 10$ an optimal decision would also result in a visit to $L_{i(10),j(10)} = L_{a,b}$. In that case at $k = 20$ an erroneous unchanged yield value was used, as the yield $Y_{a,b}$ needs to be adapted, because as the robot will move forward in time, it will first visit $L_{a,b}$ at $k = 10$ and return to this location at $k = 20$. Then the yield associated with location $L_{a,b}$ at $k = 20$ is not determined in the correct way, and in this solution procedure it cannot be changed, yielding a potentially sub-optimal solution. Instead, the yield value associated with location $L_{a,b}$ at $k = 10$ is modified using Eq. (3).

```
k = N-1
WHILE k > 1
  FOREACH L_{i,j}
    Determine all admissible u_k
    FOREACH u_k
      IF L_{i,j} is visited between k and N THEN
        Determine Δk
        Calculate Y_{i(k),j(k)} taking into account Δk
      ELSE
        Determine Y_{i(k),j(k)}
      ENDIF
      Determine V_{k+1}(x_{k+1})
      Determine R_{i(k),j(k)}
      Calculate C_k(x_k,u_k) from Y_{i(k),j(k)} and R_{i(k),j(k)}
      Calculate V_k(x_k,u_k) from C_k(x_k,u_k) and V_{k+1}(x_{k+1})
    END FOREACH u_k
    Select the u_k with the highest V_k(x_k,u_k)
    Store this u_k and V_k(x_k) for this L_{i,j} at this k
    Copy the list of visited x from x_{k+1} to x_k
    Add x_k to the list of visited x
  END FOREACH L_{i,j}
  k = k-1
END WHILE
```

The modified DP algorithm described above is used to calculate suboptimal solutions. The algorithm has the following structure:

Executing this code, for a given problem situation, results in a matrix containing the best successive location for each location at each moment. Specifying a starting location and −time then automatically results in a collection path for the robot.

4. Simulation based performance evaluation of (automated) egg collection

4.1. *Simulation of a daily production of floor eggs*

In the evaluation procedure, the quality of the found strategy or path was compared with the collection method used by a farmer, based on data about location and moment of lay of the floor eggs. As this data was not available from practice, it was obtained by making a realisation of the floor egg potential map described in section 2.3. To produce this realisation (resembling a daily production of floor eggs), 3 components were required: 1) the spatial distribution of floor eggs in the housing, given by the floor egg potential map in Fig. 3; 2) the distribution of egg-laying within a day, given by Fig. 4; 3) the number of floor eggs per day (depending on age of animals), given by Fig. 5. Based on this information, the number of floor eggs for the current day was determined. Next, for each floor egg, a location and a moment of lay were randomly selected and stored. This procedure was run for 450 days in a row (covering an animal age between 17 and 82 weeks). For each day, it was repeated 200 times to investigate and rule out random effects, resulting in 90,000 realisations of a daily production. In each realisation, on average 198 eggs were present. In total, this resulted in a set of 17.8 million eggs, with for each egg a location and a moment of lay.

4.2. *Assumptions and choices with respect to the collection paths*

Next, robot collection paths were generated to evaluate the path planning strategy. These paths were defined by selecting a starting time and position. For t = 0 five starting locations were selected to retrieve five collection paths. These five starting locations (and paths) were selected to investigate influences of the starting point on collection quality and were distributed over the housing area (Fig. 3). It was assumed that the robot covered a single cell at a time and detected and collected all floor eggs present solely in this cell.

The collection path of the farmer was based on and is largely similar to the path as used in practice. As the farmer only can reach below the housing interior but not pass through or below it, he is bound to follow the pathways in the house. For reasons of simplicity, it was assumed that the collection round of the farmer is completed infinitely fast at the start time, and thus collects all floor eggs present in all cells at the same time. In the comparison, 1 to 4 collection rounds per day were used. The start times are given in Table 1.

In the evaluation, only the area between rows A and E in Fig. 1 was taken into account, as only this area was accessible

Table 1 – Start time of farmer's collection rounds.

Name	Rounds	Start time of round			
		1	2	3	4
Farmer 1	1	11:00			
Farmer 2	2	10:00	14:00		
Farmer 3	3	9:00	11:00	15:00	
Farmer 4	4	7:00	9:00	11:30	15:00

for the robot. Furthermore, it was assumed that the robot could change between compartments only through specific corridors in the middle of the house (indicated by purple bars in Fig. 3) and that the full path was completed without stops.

4.3. *Determination of the results*

Performance of collection paths of the robot was compared with the performance of the collection paths of the farmer based on four indicators: 1) Calculation of the objective function for both situations; 2) Calculation of the time eggs are present in the housing; 3) Visit frequency on each location, in combination with the potential on this location; 4) Visual inspection of the collection path, with respect to visiting frequencies, visiting moments and coverage. For indicator 2, each path was evaluated on the complete set of production realisations, being 450 consecutive days with each 200 repetitions of, on average, 198 eggs.

The objective function in indicator 1 was the same as Eq. (4). Robot paths were planned based on this value, and farmer paths were assessed on the same indicator. Since the problem was formulated as a maximisation problem, a higher value of this indicator was regarded as beneficial.

The calculation of the (total) time eggs are present in the housing as used in indicator 2 was:

$$\text{Egg time(egg)} = t_{\text{collection}} - t_{\text{lay}} \quad (8)$$

where $t_{\text{collection}}$ is the moment of collection and t_{lay} the moment of lay of each individual floor egg. The total is calculated by summing the egg time for all individual eggs. This indicator is related to the original objective of the path planner: the requirement that egg should be collected as soon as possible after laying, since egg quality decreases with time on the floor. Thus, a lower value indicates a more useful collection path.

In indicator 3, the visit frequency for each location and potential was determined. More visits on a location with a higher potential on floor eggs is likely to have a higher preventive value and is thus regarded more useful.

With indicator 4 the behaviour of the collection paths was assessed in a qualitative way. In this method, the visiting behaviour was inspected on: 1) the first and last moment of visit for each location, to see which locations were visited early and which were visited only later on the day; 2) the number of visits on a specific location, as more visits will lead to a shorter egg time and decrease the chance on (additional) floor laying; 3) the visit frequency in the neighbourhood of a location, as increased visits have a preventive effect by disturbing birds in the surrounding of the location visited. Based on this information, a general practice-based opinion was formulated on the usefulness of a certain path.

To test statistical difference between the quantitative results of indicator 2, an ANOVA test was applied in Genstat 15. For this, egg times from individual eggs were used, and the percentiles (5, 25, 50, 75 and 95%) of their distribution were determined for every 14th day from day 7 to 441 ($n = 32$) and every 10th repetition ($n = 20$). Variation was analysed for effects of collection method.

5. Results

5.1. *Inputs for the path planning strategy*

The main input for the path planning strategy was the yield map containing the initial yield $Y_{i,j} = P_{i,j}$ for each location $L_{i,j}$, which is shown in Fig. 3. In this figure, purple dots indicate the starting points of the robot with their coordinates, while the purple squares indicate the robot passage ways between sections.

5.2. *Resulting path*

The resulting path for starting point 1 is shown for part of the house in Fig. 6. The structure of the path shown is representative for the rest of the house. An animation showing the path in more detail is given in Movie 1. It can be observed that the path was only able to access the inner part of the house (some 7200 locations) and that it traverses this area in an unstructured way. The density of lines was highest in corners, indicating that the robot path visited these locations more often compared to the middle part of the house where line density was low. Furthermore, some locations with very low yield in the middle of the housing remained unvisited.

Supplementary Video related to this article can be found online at http://dx.doi.org/10.1016/j.biosystemseng.2014.03.005.

The path of the farmer is shown in Fig. 7, indicated by a green line. The house interior dictated that he followed the corridors (as passing below the housing interior like the robot did, was not possible) and thus traversed the house longitudinally. As he used a gripper stick to collect the eggs, he was able to cover all locations that were lying within 1 m from the path.

5.3. *Evaluation of resulting paths*

The results for indicators 1 and 2, the objective function and the egg time, are given in Table 2. The starting point of the robot path seemed to have no influence on the results (yields are around 37,280 for all robot paths), but repeated collection by the farmer had a clear advantage, both on the objective function (yield between 24,400 and 33,800) and the egg time (between 1.2 and 3.5 h). Variance analysis showed that egg times were similar between robot paths (around 2.4 h) and proved a difference between robot collection and farmer collection, as well as between multiple farmer visits ($P < 0.001$). It can be observed that the robot path outperformed the farmer on indicator 1, the objective function, with at least a 10% difference. With respect to indicator 2,

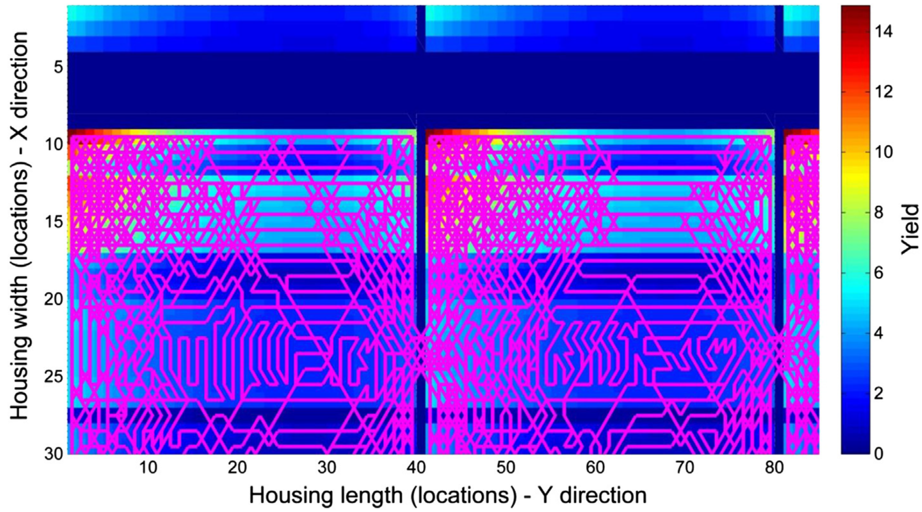

Fig. 6 – Detailed robot egg collection path 1, resulting from the path planning procedure, in part of the house and starting at starting point 1. The purple line indicates the path, which started from the top left corner. The structure of the path shown is representative for the rest of the house.

however, the robot paths were comparable to 2 collection rounds from the farmer.

The results of indicator 3, the visit frequencies, are shown in Fig. 8. It can be seen that the farmer visited all locations with equal frequency, while the robot adapted its visit frequency to the potential. Locations with a low potential were on average visited a little over once, while locations with a high potential reached an average of 14 visits. The point of equal visits by farmer and robot was found at a potential of 5, when both visit a location 4 times. When the farmer performs less collection rounds, and thus visits location less frequently, the advantage of the robot is greater.

When assessing the paths according to indicator 4, we observed that the path first focused on areas with a high potential, which were visited within 1800 cell transitions (1 h). Soon, the path also started to cover areas with little lower potential, and after some 10,000 cell transitions (about 5.5 h after the start), the path also visited areas with a low potential, like the middle of the housing. During this period, the path kept re-visiting the locations with higher potential, with a frequency depending on the potential. The path itself lacked a clear structure, and showed some random behaviour. It should be noted that areas (containing multiple locations) with a high potential will be fully covered only after several visits. By repeatedly visiting these areas, all locations were given attention and the chance on (additional) floor laying was decreased. Locations with a high potential were visited up to 17 times, while the number of visits to an area with high potential was even higher. The choice of the starting point only affected the first few

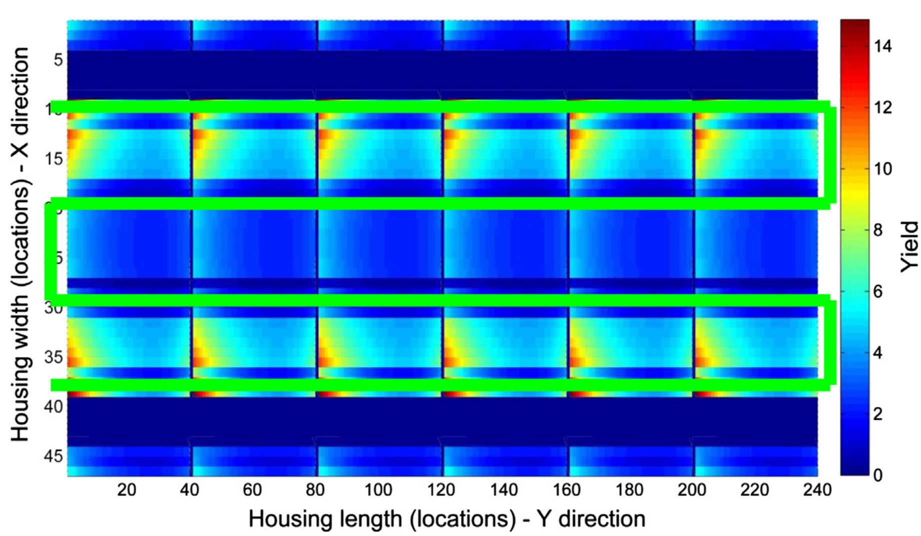

Fig. 7 – Farmer's egg collection path, indicated by the green line.

Table 2 – Results for indicators 1 and 2. Significantly different egg times ($P < 0.001$) are indicated with superscript letters (a–e), and were found between the robot paths and the farmer, as well as among the egg times of the farmer.

	Indicator 1	Indicator 2	
	Objective function (–)	Egg time (h)	
		Mean	Sd
Path 1	37,282	2.39[a]	0.32
Path 2	37,283	2.38[a]	0.32
Path 3	37,279	2.39[a]	0.32
Path 4	37,279	2.38[a]	0.32
Path 5	37,277	2.38[a]	0.32
Farmer 1	24,418	3.49[b]	0.43
Farmer 2	28,450	2.21[c]	0.25
Farmer 3	32,147	1.59[d]	0.18
Farmer 4	33,768	1.20[e]	0.14

hundred cell transition since the remainder of the paths were the same.

6. Discussion

6.1. *Model assumptions*

The map describing the distribution of floor eggs only contains an initial situation, which is the best guess given current knowledge. However, adaptability to practical conditions (including animal behaviour) is most likely improve the quality of the map. With respect to the path planning, the results under such conditions are expected to be at least as good as those presented in this paper. Furthermore, by updating the map using information about the locations of the floor eggs found during the collection round, this basic representation can be adjusted to the specific situation for the particular housing situation and flock present. This is also indicated by the feedback loop in Fig. 2. In this way, an adaptive path planning system can be constructed that reacts actively to (changes in) animal behaviour.

DP was chosen as the method for solving the path planning problem as it was expected to outperform other graph-based methods like A* (Hart, Nilsson, & Raphael, 1968) on aspects such as sensitivity for local optima, relative efficient calculation with a fixed time to an (optimal) solution and the availability of feedback data. These assumptions, however, were not yet verified, and modifications required to make dynamic programming approach suitable for our application might have affected its performance with respect to the other methods. It might be interesting to compare the current approach with other methods to see whether the advantages of DP remain in our approach.

The chosen path planning approach enabled us to limit the number of calculations necessary to come up with a feasible path for the collection procedure by considering only optimal future trajectories. However, the adaptations made to the original yield function and objective function led to violation of the Markov-property. This means that optimality can no longer be guaranteed for the current implementation. A workaround to this problem is possible, by including the complete future trajectory into the formulation of the current state (Sniedovich, 1986), but the required calculation effort will be larger. Furthermore, the need for an optimum can be questioned, as the underlying model as well as reality has a certain degree of uncertainty that limits the value of an optimal solution.

6.2. *Choice of parameters*

In section 3, values were given for robot speed and collection period. These numbers were estimated based on common sense and intuition and seemed realistic. As this paper contains the first description of the algorithm and its practical application, we consider the current selection to be sufficient. In future work, it might be interesting to do further analysis on this part.

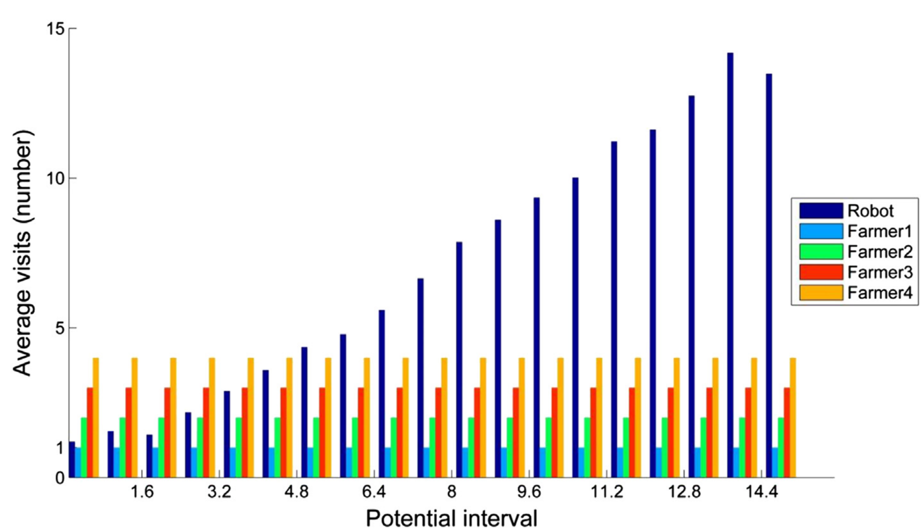

Fig. 8 – Distribution of the average number of visits to a location within a specific potential interval. Farmer visits remain equal over the potential, while the robot visits increase with potential, and can reach 14 visits for locations with a high potential.

The type and values of the objective function, the incentive and their parameters were chosen empirically, based on the desired behaviour of the resulting paths. These functions were not varied nor were their values optimised in any sense. Such optimisation might well give somewhat better results, but is not expected to be substantially different from the current results, as the non-optimality of the applied method also influenced the results.

The algorithm did not consider the effect of (sharp) turns during the path planning procedure. This resulted in a path that contains quite a number of sharp turns, of which the turning angle can be more than 300°. Such turns are physically hard to complete. Also, Choset (2001) indicates that lowering the number of turns is beneficial in both the time required to complete the path and reduction of errors. Thus, an adaptation of the cost function that results in a path with a reduced number and smaller angles of the turns might be necessary to make the calculated paths feasible for a real robot in practice.

The quantitative evaluation of the paths was based on 198 floor eggs per day, on average. This number is sensitive to variation under practical conditions. Such variation was briefly tested with the varying number of floor eggs over time and did not result in large differences in egg time, except for some cases with very few floor eggs (less than 10 floor eggs) where missed eggs had large influence on the results.

Finally, the robot speed was currently set on a low value (0.2 m s^{-1}). If a higher speeds turns out to be feasible, more locations can be visited in the same period. This will assure a faster collection of the floor eggs and probably also full coverage of the area, thereby further improving the results of the floor egg collection.

6.3. *Results*

The resulting robot paths fulfilled the third and fourth requirements (on the visiting behaviour of the path) as stated in the introduction, so the procedure can be considered as being suitable for the type of problems introduced. Prevention of floor egg laying is covered by the frequent revisiting of locations, especially those with a high potential on floor eggs. The revisiting of such locations throughout the whole day, while locations with lower potential are visited only at the end of the day, can be attributed to the incentive function, as DP alone will visit high yields in the end and lower yields in an earlier stage. If more or different control on the behaviour of the path is desired, this can be achieved by changing the incentive function or its parameters.

The currently planned paths do not reach full coverage of the area (second requirement), nor are they able to guarantee the lowest possible egg time (first requirement). This is not a major issue with respect to coverage, as the amount of unvisited locations is small (66 out of 7200 accessible locations) and the risk for floor eggs being laid there is very low. Also, the neighbouring locations were visited at least once a day, so if eggs were present, their collection in a future situation can be assured with a good detection system, which detects and collects eggs also outside the path. In fact, the current results represent a worst-case scenario, in which the robot collects only eggs in the currently occupied cell whereas the farmer collects all eggs present in a reachable neighbourhood. Thus, an improvement in the detection and collection method to collect also eggs outside the current cell will clearly benefit the robot in the comparison with the farmer. Although the egg time results were not the lowest possible, they were still comparable with the egg time values of the farmer. Lower values are only possible if the number of visits is increased further or when the location of the eggs is more accurately known so eggs can be collected faster. For the latter, adaptation of the potential map and thus the resulting paths to current practical conditions might be a good solution. Also, an increase of the robot speed (in this research 0.2 m s^{-1}) might lower the egg time.

For the collection procedure of the farmer, full coverage was assumed. In practice, obstructions from animals and interior elements in the field of view will lower the effectiveness of the farmer. As a result, eggs will be missed in the collection, leading to a longer egg time and weakening the results for the farmer. Furthermore, as the farmer is currently considered to collect all eggs at the same time, the practical egg time for the farmer might be somewhat higher as he collects part of the eggs at a later moment. Again, such a change will benefit the robot in the comparison with the farmer.

The moment of lay for a single floor egg is currently based on a logistic curve. As this curve has a little different shape in reality with more eggs laid early on the day, this might benefit the robot by a fast collection of eggs on spots with a high potential. On the other hand, for locations with a lower potential, egg time might increase and the farmer has an advantage from his full coverage of the area during each collection round.

So, when the generated collection path is applied under practical conditions and compared with the presented data, it can be expected that the results for the farmer are overestimated. The results for the robot on the other hand will be better than presented in this work. This is still considered a fair comparison, as it takes a conservative point of view, and thus helps to clarify the benefits of using a robot for floor egg collection. Taking all these aspects into account, it can be stated that the performance of the robot paths is at least comparable with the collection performance of the farmer, and that the structure of the robot paths offers a clear advantage.

6.4. *Opportunities*

Irrespective of their performance, the generated paths are needed and useful when taking over manual activity by robots. This is especially worthwhile for the collection of floor eggs, as this is perceived as a physically demanding job under harsh environmental conditions (Blokhuis & Metz, 1995). In a similar situation, the introduction of automatic milking systems, it was shown that limited technical capabilities are already sufficient to enable the introduction of automatic systems that take over manual work (Sonck, 1996). As a result, this research opens up possibilities for further development of a robot for the collection of floor eggs, and to extend this concept for other tasks.

With respect to the general applicability of the presented method, it can be indicated that DP as discussed in this paper (although not in its optimal form) is a good method to solve the type of problems at hand, and provides useful results. This problem type considers all cases in which (only) some form of a priori knowledge about the occurrence of an event is available, and in which there is a need for continuous spatial coverage with non-uniform revisiting of locations. It can be strengthened by the fact that the presented method applied is not limited to a certain size, shape or formatting of the area that needs to be covered, except for the requirement that all parts should be reachable. As such, the proposed method is suitable for any kind of (poultry) housing system, from traditional floor housing up to future concepts like Rondeel, Windstreek and Eggsphere (Janssen et al., 2011; Wageningen UR projectteam 'Houden van Hennen', 2004; Weeghel, Groot Koerkamp, & Cornelissen, 2011). Use of this method, however, is not limited to applications in poultry or agriculture but can be extended to all sorts of applications where non-uniform coverage is desired and some a priori information about the phenomena of interest is available. Examples of other applications are surveillance tasks, collection of objects or the cleaning of large buildings and the removal of trash, like indicated for Continuous Area Sweeping by Ahmadi and Stone (2005, 2006).

A next research step would be to compare the presented method against other methods or an extreme bound, to gain more insight in the capabilities of the current algorithm. When doing so the sensitivity of the assumptions on parameters like robot speed and path length can be investigated, as well as the resulting paths in terms of egg time or number of visits to a location. Such analysis was considered out of scope for the current work, but remains an interesting field for further work.

7. Conclusions

A novel path planning method based on DP was presented for non-uniform repetitive coverage of areas. It was applied and tested by generating robot paths for the collection of floor eggs in a non-cage poultry house. In a quantitative evaluation, the resulting paths were comparable to a standard situation from practice with 2 collection rounds of the farmer. The paths clearly outperformed the farmer with respect to revisiting specific areas and the general structure of the path, by having frequent revisits to locations with a high probability. Although optimality of the results could not be guaranteed, the method and resulting paths are still considered suitable for the type of problems described. Extending the underlying model with feedback information will create an adaptive path planner that tracks also changes over time. The presented results are very promising for the use of a robot to collect floor eggs, and will result in a reduction of the demand for manual labour.

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