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Assessment of Track Sequence Optimization based on Recorded Field Operations

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ABSTRACT

The sequence of working the parallel lines in agricultural field area coverage operations can be optimized to minimize the total non-productive time. The amount of savings achieved in using the optimized sequence, denoted the B-pattern, compared to the conventional sequence varies considerably depending on the operation's features. This work presents a method for estimating the savings of using B-patterns and is applied on a specific problem instance consisting of a specific tractor, implement and field, based on a recording of a "conventional" operation.
The savings assessment method consists of fitting a turn model using data from the recording, generating the Traveling Salesman Problem (TSP) cost matrix with turn model, solving the TSP and finally using parts of the recording to estimate the savings. The specific problem instance was a harrow operation with an estimated savings of 3.3% in total operation time.

Keywords: B-patterns, track sequence optimization, monitoring, Dubins curves, Traveling Salesman Problem, Denmark

1. INTRODUCTION

In the majority of agricultural field operations, a machine treatment covers the entire field by following parallel tracks and turning between them in the headland. As it has been shown, for "neutral material flow" field operations, the optimal sequence of working the tracks minimizing time can be modeled with a Traveling Salesman Problem (Bochtis 2008; Bochtis & Sørensen 2009). The optimal track sequence depends on the problem instance data, including the geometric layout of tracks, the machine kinematics, the working width, and the desired start and ending locations of the operation. The task time savings of using the optimal track sequence, denoted the "B-pattern" instead of a "conventional" sequence, was studied by simulating a series of different problem instances where the turning radius and working width was varied (Vougioukas et al 2010). This specific study showed task time savings in the range 8.4-

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17%. As the survey showed, the task time savings varies significantly depending on the specific problem instance and the already used sequence, so it can be difficult for the farm manager to know what the actual level of savings would be by applying B-patterns.

This work presents a procedure for the estimation of the expected task time savings derived from the optimization of the track sequence that is based on the analysis of the GPS-recordings of the operation.

2. ASSESMENT METHOD

The time savings of using an optimized sequence can be computed as:

$$\text{savings} = \frac{\text{Duration of normal operation - Duration of optimize operation}}{\text{Duration of normal sequence}}$$

The time working a field consists of a working part where the soil (or the crop) is treated and a non-working part where the machine makes maneuvers like the turnings and other travel where the soil (or the crop) is not treated.
The working part, denoted $\mathrm{t_w}$, is constant (in terms of the travelled time), but the non-working part varies depending on the sequence of working the tracks. We denote the non-productive time as a function $\mathrm{t_n}(s)$ of the sequence of working the tracks, s. The sequence observed in the recording is denoted s^{r} and the optimal sequence is denoted s^*. The savings is then computed as:

$$\text{savings} = \frac{\mathrm{t_n}(s^{\mathrm{r}})+\mathrm{t_w} - \left(\mathrm{t_n}(s^*)+\mathrm{t_w}\right)}{\mathrm{t_n}(s^{\mathrm{r}})+\mathrm{t_w}} = \frac{\mathrm{t_n}(s^{\mathrm{r}})-\mathrm{t_n}(s^*)}{\mathrm{t_n}(s^{\mathrm{r}})+\mathrm{t_w}} \quad \text{(E.g. 1)}$$

The time of the non-working part $\mathrm{t_n}(s^{\mathrm{r}})$ and the working part $\mathrm{t_w}$ can be measured from the recorded path. The remaining unknown is the time of the non-working part using an optimal sequence $\mathrm{t_n}(s^*)$. The optimal sequence and the time of it, can be found if a model of the function $\mathrm{t_n}(s)$ is known.
It is however impossible to estimate the “summed-time-of-all-turns” function $\mathrm{t_n}(s)$ using the recording of a single operation. Instead it can be shown that it is enough to estimate the “time-of-an-individual-turn” function $\mathrm{t_{turn}}(c_{\mathrm{i}}, c_{\mathrm{f}})$, where c_{i} and c_{f} is some representation of the vehicle state at the beginning and end of a turn. From the recordings we can extract many turns needed for the model fitting of this function.

2.2 Turn Model

The turn model is based on Dubins curves because of the low computational time and memory requirements while it still models the minimal turning radius present in most agricultural machinery steering systems (Dubins 1957). The input to the shortest Dubins curve function is the initial and final pose, and the minimum turning radius of the vehicle. The output is the determination of the shortest path connecting the initial and final poses using straight and circular arcs, and its corresponding length.
To achieve a model outputting time, the path length is divided with a speed. Furthermore it is beneficial to add a constant or *offset* to the length of the path.
The turn time model becomes:

$$t_{turn}(x_i, y_i, \theta_i, x_f, y_f, \theta_f) = \frac{d(x_i, y_i, \theta_i, x_f, y_f, \theta_f, R) + o}{v}$$

The model parameters are the minimal turning radius, R, the offset, o, in meters and the speed, v, in m s^{-1}. The function $d(\cdot)$ is the path length in meters of the Dubins curve. The model input is the initial pose, $\{x_i, y_i, \theta_i\}$, and final pose $\{x_f, y_f, \theta_f\}$.
A version of the model which returns the distance is also used:

$$d_{turn}(x_i, y_i, \theta_i, x_f, y_f, \theta_f) = d(x_i, y_i, \theta_i, x_f, y_f, \theta_f, R) + o$$

Computing the shortest Dubins curve is done by taking the shortest of all eight possibilities (See Shkel & Lumelsky 2001 for more details on computing the various possible paths).

2.3 Aspects in fitting turn model to data

The model fitting process consists of finding the parameter values which minimize the sum of the residuals, i.e. the differences between the measured turn and the modeled turn. Each turn is a *data point* in model fitting terminology and we must find these in the recorded path of the machine. Standard least squares fitting were used.

It was desirable to fit both *time* and *distance* in the fitting process. However in this multi-objective fitting, the two different types of residuals must be weighted in order to equalize their importance. The distance is included to gain some *regularization* to the fit to prevent overfitting. Overfitting means that the best fit can be achieved with many different sets of parameter values.

We characterize the turns in relation to how many tracks are skipped when driving from an initial pose to the final pose. For example the turn from a track to another track directly adjacent to it, is denoted a *skip zero turn,* and the turn from a track to another track where the adjacent track is skipped, is denoted a *skip one turn*.

In many cases the recording of an operation includes an uneven distribution of the count of various skip turn types. To ensure that the model is equally accurate for the various skip types, the residuals of each turn type must be weighted somehow in relation to the distribution. If very few turn samples exist of a certain turn type the weighting should not be too high to prevent the case that a single outlier of that turn type is given too much influence.

2.4 Finding the optimal track sequence

To find the optimal sequence of working the tracks minimizing the non-working turning time the TSP approach from Bochtis 2008 and Bochtis & Sørensen 2009 is used. The turn time model is used to generate the cost matrix of the TSP and it is solved with the open source LKH TSP-solver (Helsgaun 2009). It should be noted that the speed and offset parameter of the turn time model does not affect the optimal track sequence because they occur as constant scaling and addition in the elements of the cost matrix.

3. USE OF ASSESMENT METHOD ON EXERIMENTAL DATA

3.1 Recording operation and segmenting path

The path of a tractor harrowing two adjacent fields were recorded with 1 Hz sampling frequency using a GPS logger placed in the window of the tractor. The field area was 21 ha and the operation took 2 hours and 20 minutes. The tractor was a belt-driven Caterpillar Challenger and the implement was a Horsch Terrano 12 FG harrow with 12 m working width (See Figure 1).

Figure 1 - Tractor and harrow implement used in recorded operation. GPS logger was placed in the window of the tractor.

The recorded path is segmented into working parts: tracks and headland and non-working parts: turns and "field exit travel". The identification of the point on the trajectory that separates a turn and a track is arbitrary to some extent. The separated turns are used in the fitting of the turn model, so the offset parameter will compensate for the choice of separation point. It is thus important to be consistent, for example by

choosing a point which is closest to the path of the innermost headland pass (See the left insert in Figure 2).
Some parts might seem to fit neither of the grouping types, however they can usually be included as part of a track. The path around the obstacle in the lower field is included as part of the associated track, as is the odd eight-digit-shaped path in the upper field.

The ending of each track is given a unique identifier and the sequence of visiting them in the working of the tracks defines s^r.

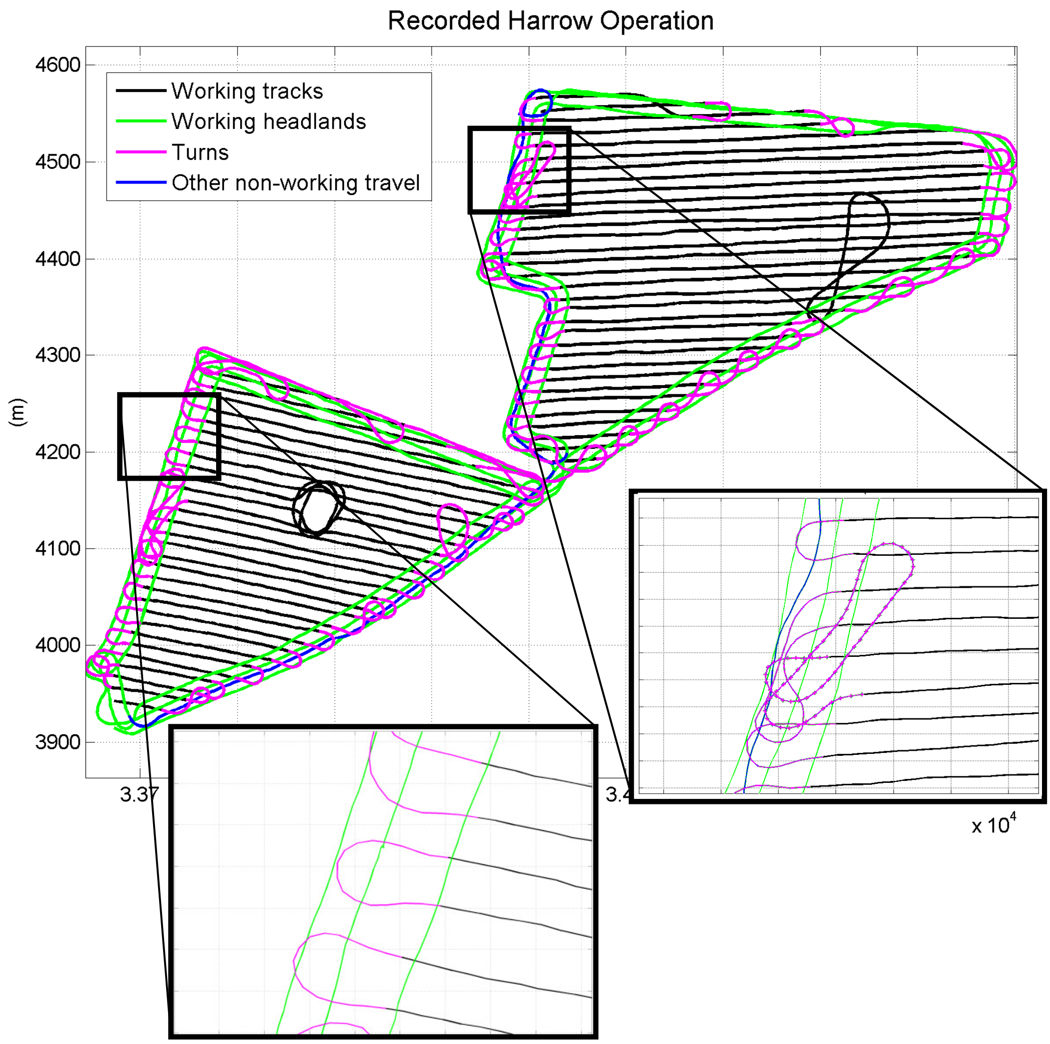

Figure 2 - Plot of the segmented recorded path of the tractor. The left insert shows how turns are defined as starting at the innermost headland pass. The dotted pink path in the right insert is an example of a turn outlier which should not be included in the turn model fitting.

3.2 Fitting the Turn Model to data

From each turn we collect the initial pose, final pose, time and distance. The initial and final pose are inputted in the turn model to achieve a modeled time and distance. In order to do the multi-objective fitting, the time is weighted according to the ratio between the mean of the times and the mean of the distances which is around 3.65.

Most of the turns are *skip zero turns*, however to achieve a good model we need more samples of the other types: *skip one*, *skip two* etc. These were collected from other fields that the machine was working the same day.

In order to achieve equal influence on the model, the various skip types are weighted according to their count. The skip three and four types gets a lower weighting because there are very few data points in those groups and an eventual outlier will have too much influence. The weightings for skip zero, one, two, three and four are respectively 30%, 30%, 30%, 5% and 5%.

The collected turns and the resulting fitted turn model using least squares fitting is shown in Figure 3. Notice that the turning time of the fitted model is lowest for *skip one turns*. The fitted model has a turning radius of 7.7 m, speed of 3.6 m/s and offset of 20 m.

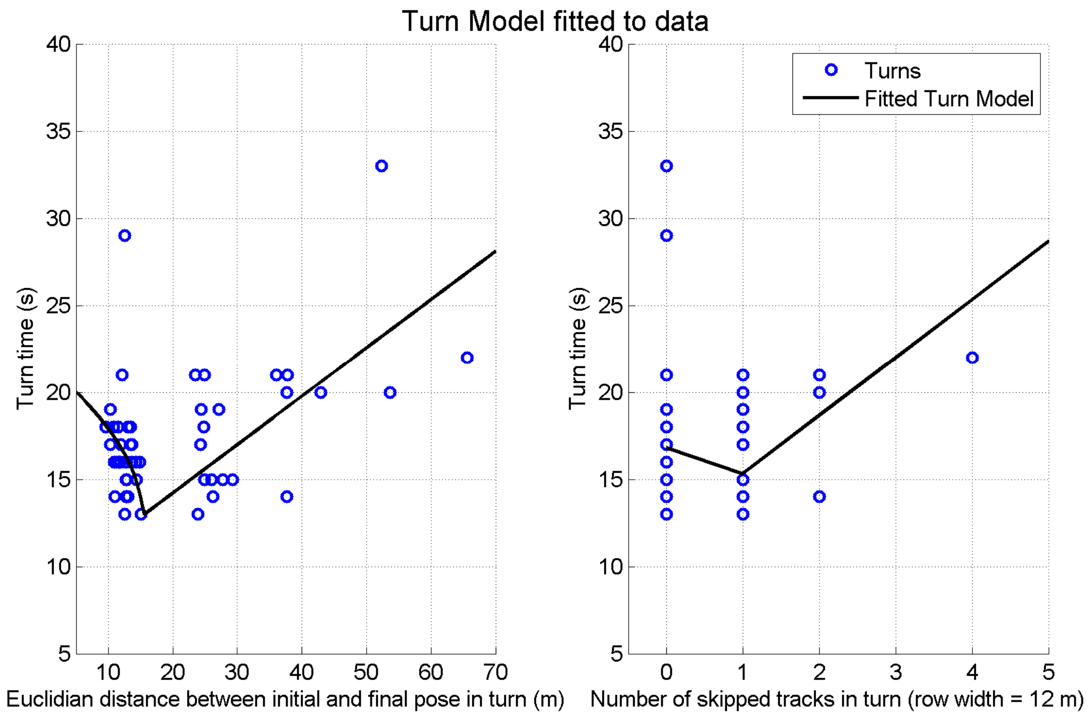

Figure 3: Collected turns and the fitted turn model. Turns are collected from the recording seen in Figure 2 and from some other recordings of the same machine and working conditions.

3.3 Finding optimal sequence and estimated savings

We use the fitted turn model to generate the TSP cost matrix. As said in section 2.4, the speed and offset has no influence on the optimal sequence itself, only on the time of the optimal sequence.

The LKH TSP-solver returns an optimal TSP solution which is used to generate the optimal sequence of working the tracks s^*. The modeled optimized turning time $t_n(s^*)$ is computed using the fitted turn model.

The difference in sequence between the recorded and the optimized sequences is illustrated in Figure 4 of the upper field. As can be seen more of turn type *skip one* are present in the optimized sequence as is expected when skip one turn is a minimizer of the turn model as seen in Figure 3.

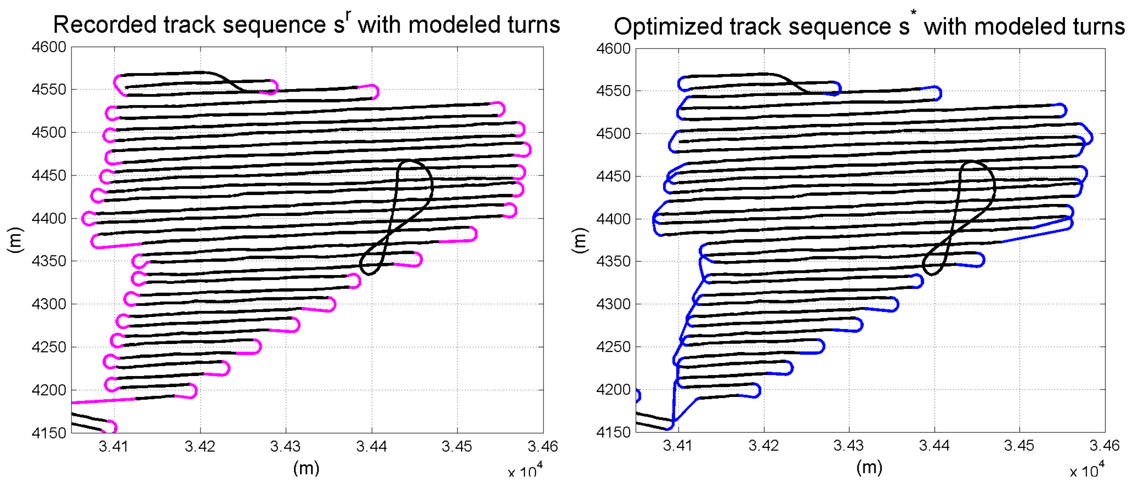

Figure 4 – The left plot shows the recorded sequence with modeled turns. The right plot shows the optimized sequence with modeled turns.

The time spent in working tracks, headlands and the non-working turns and field exit path for the recorded operation and the optimized operation are shown in Figure 5. The absolute savings is 4.3 minutes and the relative savings are 3.3 %.

5. CONCLUSION

This work presents a method for estimating the savings of implementing an optimized field area coverage planning, in the particular case the B-patterns. The method was applied on a specific problem instance consisting of a specific tractor, implement and field, based on a recording of the corresponding "conventional" operation.
A turn model was fitted to turn collected from the recording and the found model seemed to fit the data well.

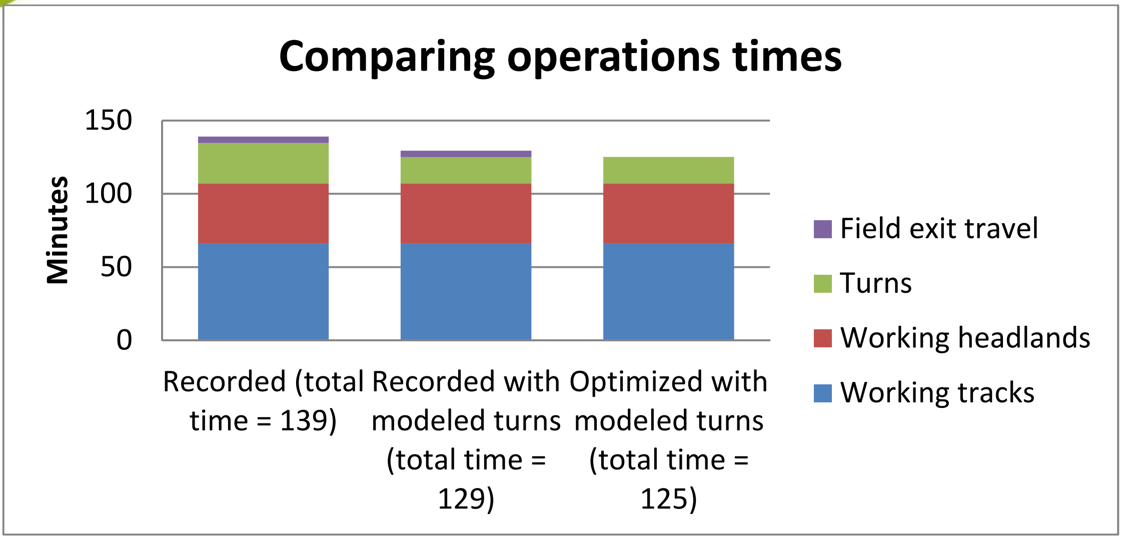

Figure 5: Absolute savings are 4.3 minutes and relative savings are 3.3 %.

6. ACKNOWLEDGEMENTS

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