A NOVEL APPROACH FOR HOLISTIC OPTIMIZATION OF MOBILE MACHINE MANAGEMENTS

Timo Kautzmann (Email: Timo.Kautzmann@kit.edu)
Marcus Geimer (Email : Marcus.Geimer@kit.edu)
Karlsruhe Institute of Technology
Chair of Mobile Machines
Germany

Micaela Wuensche (Email: Micaela.Wuensche@kit.edu)
Hartmut Schmeck (Email: Hartmut.Schmeck@kit.edu)
Sanaz Mostaghim (Email: Sanaz.Mostaghim@kit.edu)
Karlsruhe Institute of Technology
Institute of Applied Informatics and Formal Description Methods
Germany

Maurice Bliesener (Email: Maurice.Bliesener@bucherhydraulics.com)
Bucher Hydraulics, Klettgau
Germany

ABSTRACT

The development of modern mobile machines is aimed to facilitate a large degree of freedom for designers and engineers to optimize the system according to their individual goals. However, current management strategies generally use little of evolving potentials and machine operation is highly influenced by the skills of the operator. We present a novel approach to consider the mobile machinery as a whole and employ a holistic optimization to reduce the fuel consumption. This is realized by the Observer/Controller architecture. Currently a model of the demonstrator, a *Fendt Vario 412*, was designed to test and verify developed modules of the architecture. First results will be presented. This interdisciplinary project is called *OCOM-Organic Computing in Off-highway Machines* and is funded by the *German Research Foundation (DFG).*

KEYWORDS: Machine Management, Adaptive, Holistic Optimization, Organic Computing

1. STATE-OF-THE-ART MACHINE MANAGEMENT

Over the past decades, the development of mobile machines is influenced by a rising amount of internal degrees of freedom. In [1,2] novel concepts for drive trains in self-propelled agricultural machineries are introduced. In both cases mechanical constraints between axis and wheels are dissolved by using individually controlled hydraulic motors. In 1995, the continuously variable transmission has been introduced in tractors. Since Agritechnica 2009 in Hannover, Germany, the distribution of continuously variable transmissions is not restricted to tractors of medium and high power any more. There are several indications [2] that their distribution farther advances due to environmental legislation. Another recent development in this area is the infinitely variable power takeoff (PTO) [3]. This concept is based on the electrically assisted drive train in tractors. There, a power electronics center converts the electric power according to the load situation and the demands of the operator between crankshaft generator, e-machine within the infinitely variable PTO transmission and further electric consumers (fan, compressors and pumps). These consumers are powered independently of crankshaft revolutions per minute (rpm) – another degree of freedom in such a system. According to [4] there will also be hydraulic solutions for running these consumers independently of crankshaft rpm in mobile machines. In addition, [4] predicts a deeper integration of decentralized electronic directly into the single components of mobile machines. The On-Board-Electronic (OBE) uses integrated components to collect and send important data to a centralized controller. In this way, by removing mechanical constraints, components can be controlled individually and thereby increase degrees of freedom.

The list of examples for a rising amount of degrees of freedom is not completed, even though it provides an overview over recent developments in this area. Reasons for the introduction of these new technologies are basically a higher comfort and a more efficient operating of components. According to [5] a high variability in the individual drive train and networked communication are basics for consequent optimization.

The developed solutions offer many possibilities for controlling to be set by an adequate management strategy. A machine management specifies the amount of all machine components realized as hardware and software, necessary to fulfill the intended but variable goal in an organized way. In contrast, an operating strategy designates the methodology used to fulfill an adaptable, at any time variable goal. Stationary, quasi stationary and dynamic approaches are possible, cp. [6]. Conventional strategies use static characteristic maps to individually control single degrees of freedom. The simplest alternative to conventional strategies in mobile machines with continuously variable transmissions is to run the engine at a constant nominal speed. Vehicle speed is adjusted by adapting the transmission ratio via a closed-loop controller. This control is well known for machines with little power consumption in the drive line, e.g. combines or excavators and for tractors in the power take-off (PTO) mode. Conventional control of wheel loaders is governed by the operator using the throttle, brake, and inching pedals as well as a direction command lever. The transmission ratio is varied in dependency of the engine speed. Conventional strategies in tractors use the throttle pedal and the control lever to individually control engine speed, transmission ratio and flow rate of the working hydraulics. Or the operator may set vehicle speed by throttle pedal. Engine speed and transmission are set in a defined ratio. Adjusted flow rate is closed-loop controlled.

Figure 1 illustrates a generalized conventional management strategy for mobile machines. An operator sets basic defaults which are given as inputs into static characteristic curves or arrays in order to find optimized command variables for the single subsystems for some predefined cases. Basically, command variables of one subsystem are individually set without considering the settings of other subsystems and the interaction between them. The output of each subsystem is accumulated to a target working result that is measured and controlled by the operator.

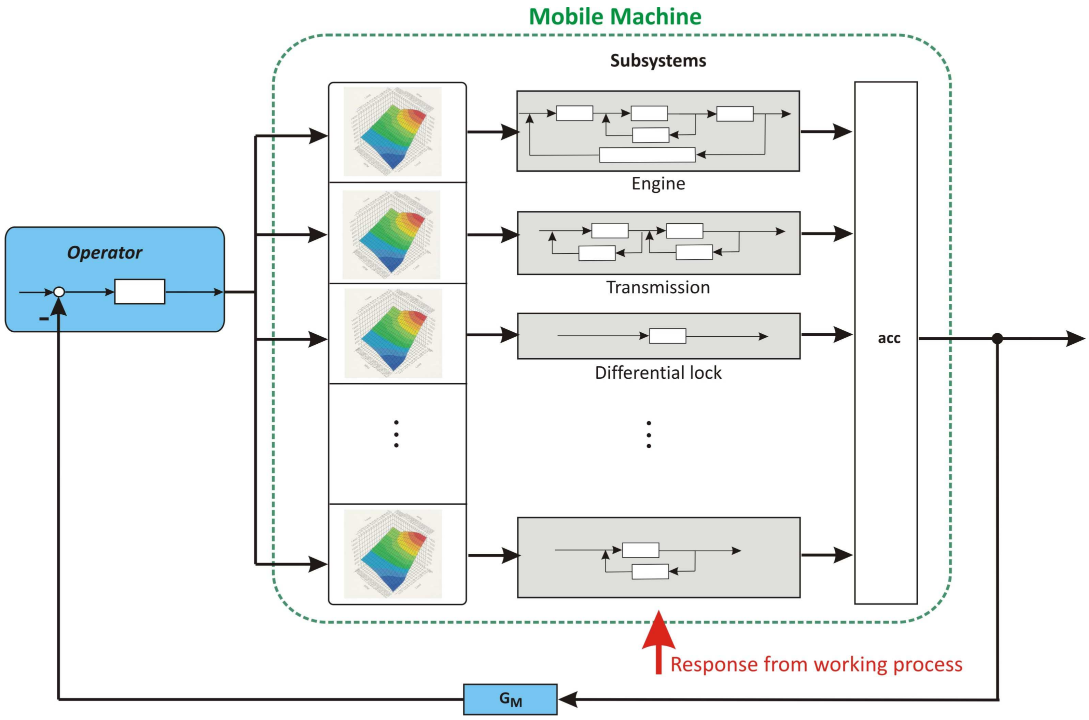

Figure 1. Conventional Machine Management

2. NEW APPROACH

A mobile machine is a complex and cross-linked system. Changes in one component may lead to entirely new overall system states. For this reason, recent research projects show significant potential capacities in a simultaneous optimization of several components compared to conventional management strategies. In [7] engine and transmission are collectively controlled to realize a so called *Power Control* that is able to reduce fuel consumption up to 16 %. The engine overloads in a specific way due to actuator signal gear ratio of the transmission. In [8,9] research projects are presented that collectively control engine and working hydraulics by the use of the CAN-BUS. Basically the information about the power instantaneously needed by the pump is measured by the pump control unit and passed directly to the engine control unit for a proper engine regulation. According to [8,9] significant reduction of fuel consumption can be realized. So far, the most extended collective control is presented in [10]. Here, tractor and certified implements exchange information bi-directionally based on current ISO-BUS implementation level and a protected communication level to optimize the entire system. With that system, several parameters can be automatically controlled by the tractor-implement system to optimize the process focusing on productivity, cost reduction, operator comfort or better work quality. According to [4] an even more intense and direct communication between single components will be necessary to further increase efficiency.

Most of mentioned research projects are realized in agricultural machinery and especially in tractors. Agricultural engineering has always been a motor for new technologies in the area of mobile machines. However, new technologies influence the entire mobile machine area. For instance there have been some recent efforts to optimize engine and transmission simultaneously in wheel loaders or excavators [11,12].

Although there has been much improvement towards automation and optimization especially due to the adoption of extensive electronics, working results are determined particularly by the experience and the skills of the operator [7,13]. Apparently, existing automatic management strategies are not able to optimize all possible working cycles [14]. Furthermore, the operator is generally not capable to optimize all degrees of freedom in engine, transmission, PTO, and working hydraulics by himself due to the complexity of simultaneously set control variables and the constantly changing operating condition. With that background, a new notion of holistic optimization will be given.

Holistic Optimization

Without loss of generality, we select a tractor as a representative for mobile machines for our examinations of holistic optimization to optimize fuel consumption in the followings.

In holistic optimization we consider the machine as a whole and try to optimize the overall functionality. A tractor has *A* internal adjustment variables denoted as vector $\vec{v}_A$, which describes the functionality within the tractor. For every $\vec{v}_A$, a vector $\vec{v}_S$ (s-dimensional) characterizes the external influences on the tractor. Both vectors $\vec{v}_A$ and $\vec{v}_S$ influence fuel consumption denoted as $b_e(\vec{v})$, where

$$\vec{v} = \begin{pmatrix} \vec{v}_A \\ \vec{v}_S \end{pmatrix}$$

according to **Figure 2** and build our search space with (*a*+*s*) dimensions.

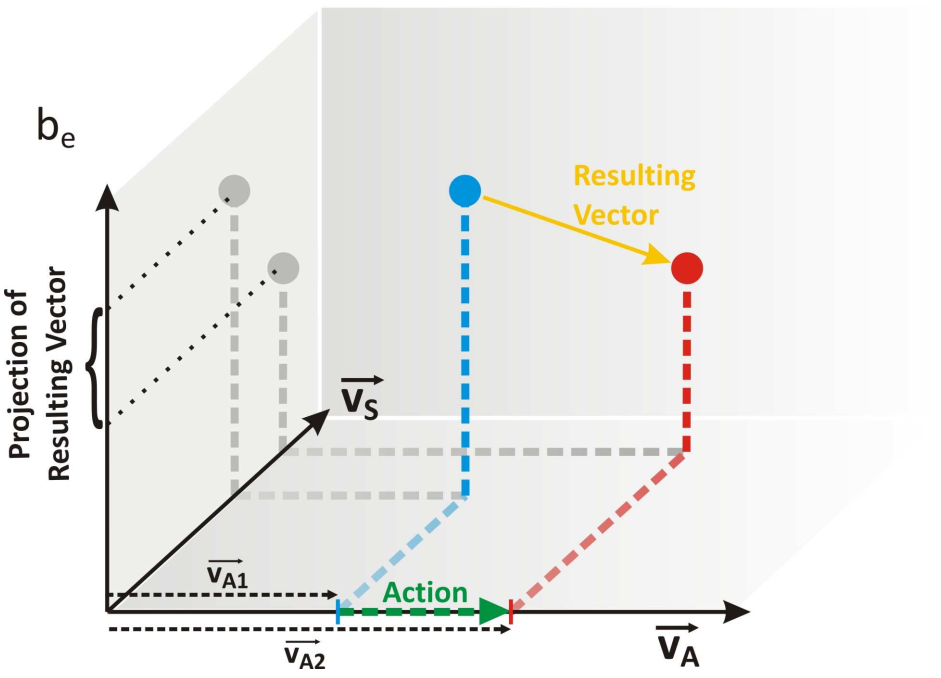

Figure 2. Holistic Optimization

Formally the optimization problem can be specified by:

$$Min \quad b_e(\vec{v}_A, \vec{v}_S)$$

Subject to $\quad \vec{v}_A \in \mathbb{R}^{A}$

$\vec{v}_S \in \mathbb{R}^{S}$

$\vec{v}_S = f(\vec{v}_A, \vec{y})$

Where be: $\mathbb{R}^{A+S} \rightarrow \mathbb{R}$ and $\vec{y}$ is a vector of partially unknown external environmental parameters that cannot be influenced by the system. f is a function indicating the dependency between $\vec{v}_A$, $\vec{v}_S$ and $\vec{y}$, i.e. $\vec{v}_S$ is influenced by $\vec{v}_A$.

The optimal solution of this problem is a vector of $\begin{pmatrix} \vec{v}_A{}' \\ \vec{v}_S{}' \end{pmatrix}$.

The goal of holistic optimization in this paper is to find entries of vector $\vec{v}_S$ that characterizes together with $\vec{v}_A$ the system state regarding b_e. Suppose, the tractor is working with $\vec{v}_{A1}$ and $\vec{v}_{S1}$ results. Now we look for an appropriate action $\vec{v}_{A2}$ that leads to $\vec{v}_{S2}$ so that we obtain a better $b_e(\vec{v}_{A2}, \vec{v}_{S2}) < b_e(\vec{v}_{A1}, \vec{v}_{S1})$. Note that we can only change $\vec{v}_{A1}$ which results in a different $\vec{v}_{S2} = f(\vec{v}_{A2}, \vec{y})$.

Now the challenge is to find a set $\vec{v}$ that entirely describes the fuel consumption b_e. As $\vec{v}_A$ is already determined by the adjustment possibilities in a tractor, our goal is to find a $\vec{v}_S$ that supplements $\vec{v}_A$ in a way that b_e is characterized. Regarding the tractor as a system, fuel consumption is determined by the power flow through the interface of a tractor and the internal degrees of freedom according to **Figure 3**.

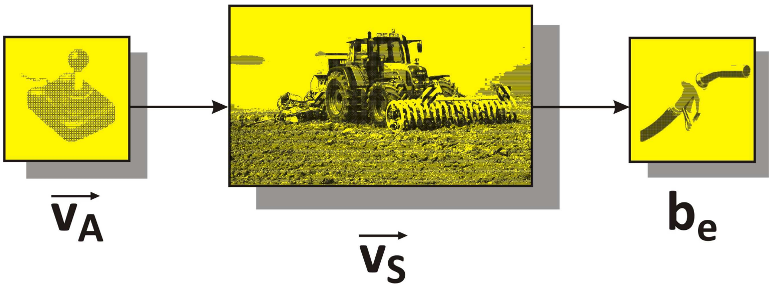

Figure 3. Influences on Fuel Consumption

The definition of holistic optimization differs from the conventional definitions, where formulation of the optimization problem focuses generally on varying some entires in $\vec{v}_A$ while trying to prevent changes in vector $\vec{v}_S$ [8,9,11,12]. This is due to the lack of an overall machine observation of common machine managements which means in particular that potentials are not entirely exploited.

In the next section, we describe a methodology to achieve above described holistic optimization.

3. METHODOLOGY

Looking for possible solutions how to realize such a holistically optimizing system, in this work experiences from other areas of research are being applied and adapted to the problem at hand. The main source of inspiration here has been the field of Organic Computing [15,16], a discipline in computer engineering concerned with achieving reliable and adaptive control of highly complex systems. In recent years, information technology is facing the challenge, that IT systems are becoming continually smaller, more widely used, and at the same time equipped with more and more "intelligence" as well as communication and cooperation abilities of their own. This leads to the formation of increasingly complex systems of a variety of interacting "agents" that communicate and cooperate in a decentralize and partly autonomous way. Facing this development, several areas of research tackle the challenge of finding structures or architectures to design such highly complex systems in a way that keeps them controllable and trustworthy for the user, and at the same time endorses a high degree of autonomy and self-organization.

In the field of Organic Computing (OC) a generic Observer/Controller(O/C) architecture has been developed that serves as a design pattern for the control of complex self-organizing systems like those described above [17,18]. Additionally in OC, a special emphasis is put on controllability by an external user of the system, and on special learning capabilities of the system itself. With respect to mobile machines fulfilling a tremendous number of different working cycles and the fact that the O/C architecture has already been successfully applied to several natural as well as technical scenarios [19,20,21,22] this makes it especially suitable as a basis to develop a machine management system that regards the machine as a whole, as is the focus of this work.

The generic O/C architecture consists of three main parts, that will be described in the context of a mobile machine (here: a tractor) in the following: the *System under Observation and Control* (SuOC), the *Observer* and the *Controller* (see **Figure 4)**.

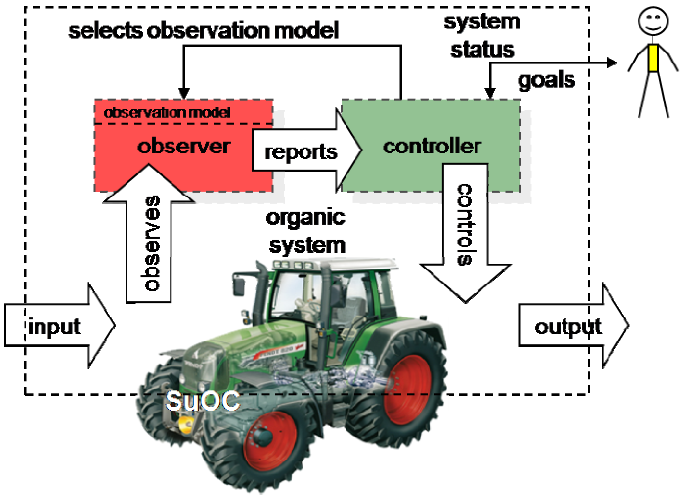

Figure 4. The Observer/Controller architecture

The SuOC represents the underlying system of self-organizing cooperating agents that fulfill a certain common task. It is completely capable to function on its own, independently of Observer and Controller. In case of a tractor, the SuOC is the entirety of its subsystems, as depicted in **Figure 1**.

The task of the Observer is to monitor all relevant data coming from the SuOC and to analyze it in order to characterize the state of the system. In the holistic machine management system that is developed in the course of this work, the tractor is to be regarded as a whole and the system state is highly dependent on internal and external influences.

Based on the system state $\vec{v}_S$ that has been identified by the Observer, the Controller implements a mapping that assigns every situation $\vec{v}_S$ a suitable action $\vec{v}_A$. Due to the emphasis of learning capabilities in the O/C architecture, the composition of this mapping is determined in two separate learning steps: *offline learning* and *online learning*. In *offline learning*, new actions can be generated by evolutionary operators (such as selection, mutation and recombination) and their effectiveness (fitness) in the given situation is tested by applying them to a simulation model of the SuOC that is an integral part of the Controller. In case of the tractor, any suitable action is a valid configuration of the actuators that influence the adjustments within a tractor. Input to the simulation model of the SuOC is the situation given by the Observer and the actuator-configuration that is to be evaluated, as well as further parameters that can be derived from those. Output of the simulation model and basis for the fitness evaluation of the tested action is the efficiency factor of the simulated system under the given conditions. In order to reduce fuel consumption, the goal is to maximize this efficiency factor. In *online learning*, the mapping learned with the simulation model will be tested on the real system. Actions are applied when the corresponding situation occurs and the resulting effects are measured and evaluated. In case of the tractor, the averaged efficiency after applying the action is compared to the averaged efficiency the system had in the given situation without interaction of the Controller. The higher the improvement that is achieved by the action, the better the rule (situation $\vec{v}_S$ → action $\vec{v}_A$) is rated. Rules with low fitness values are eventually deleted from the mapping and subsequently replaced by new ones.

4. CURRENT DEVELOPMENT STATUS

A systematic development process such as the V-Model [23] helps to generate a feasible and successful realization of the O/C architecture in the tractor. The V-Model has been proven to be a development standard for mechatronical systems. In the current project phase, the developed modules of the O/C architecture are refined and verified by employing a tractor model in AMESim (see **Figure 5**). This specific approach is called *Model-in-the-Loop (MiL)* which is meant to provide all needed sensor signals for the Observer and to simplify the realization of action signals from the Controller. After *MiL* phase the O/C architecture is meant to be adapted to a *Rapid Control Prototyping (RCP) Hardware* to control the tractor. The hardware is able to import a Matlab/Simulink model automatically by automated C-code generation. With respect to that, the O/C architecture will be implemented in Matlab/Simulink. AMESim and Matlab/Simulink communicate via so called S-functions in a co-simulation.

Input into the AMESim model is the *PowerMix* [24] of the *German Agricultural Society (DLG)*, to describe the main working processes a tractor performs. PowerMix defines traction, PTO and hydraulic power over time.

To design the AMESim simulation model, efficiency-afflicted models and a time-based simulation approach with physical loss modeling and concentrated parameters are chosen. Its specific feature is the acquisition of basically all internal and external influences on the target function fuel consumption. These influences need to be specified by the vector $\vec{v}$ in Section 2. Due to the resulting large size of the model, a classification of the entire model into subsystems *engine*, *working hydraulic*, *PTO*, *transmission*, *drive side*, and *transmission control device* is realized. To adapt correct states of wheel-soil contact, steering angle, 4-wheel clutch and differential lock in subsystem *drive side*, a 5-dimensional system of equations must be solved in Matlab. Communication is realized via *S-functions*. In *transmission control device* both power and velocity control are realized and a logical unit switches adequately between these different controllers. Moreover the simulation model is meant to provide data for the basic machine behavior to be validated in a later step, using measured data from the machine. More design details and results of the model are given in [25].

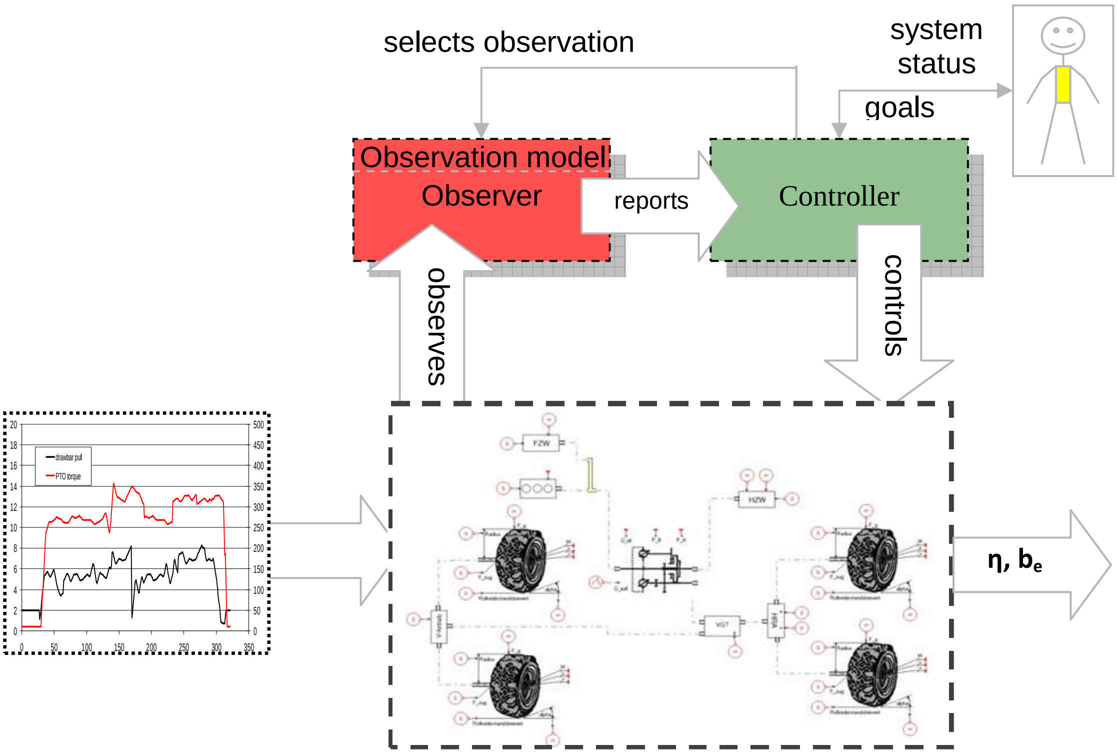

Figure 5. Model in the Loop

Task of current project phase is to find a vector $\vec{v}$ that entirely describes the situation of the machine regarding the target function. According to Section 2 this vector consists of an external vector $\vec{v}_S$ that describes the power flow over the interfaces and an internal vector $\vec{v}_A$, which describes parameter settings within the tractor. $\vec{v}_S$ will serve the Observer to get a holistic characterization of current situation and will be the basis for the Controller to later learn an action $\vec{v}_{Ai+1}$ in the mapping. Goal will be to find an approximation of optimal action $\vec{v}_A{}'$ for each single situation $\vec{v}_S$.

5. RESULTS OF THE SIMULATION

In this section, we first present selected results of the co-simulation. Input to the simulation model is the DLG-PowerMix cycle *Z7PR* [25]. This cycle describes the working process bailer. According to **Figure 6**, all output power consumers like drawbar pull, PTO and hydraulic power are active.

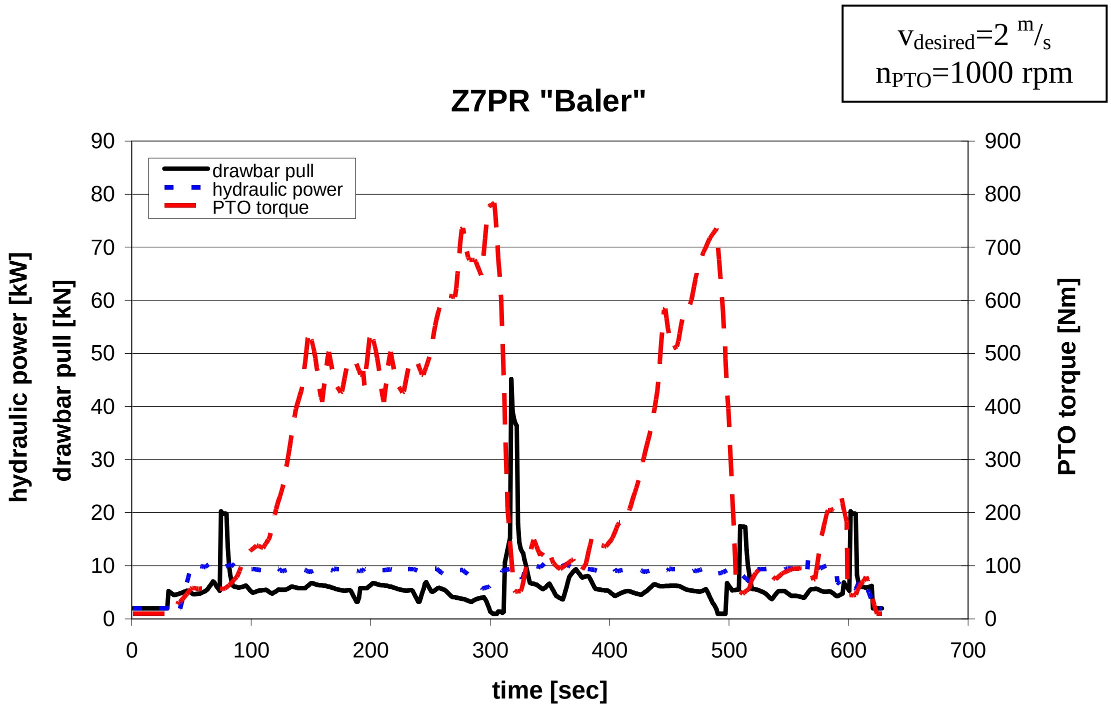

Figure 6. PowerMix Cycle Z7PR (according to [25])

Total power demand of Z7PR is 100% of available engine power. This means that the operating point of the engine is located at the full load characteristic mostly all of the cycle time according to **Figure 7** (left). In cases of engine overloading exceeded 14 % of nominal rpm the controller switches from speed control to power control. In that case desired speed of 2 m/s collapses according to **Figure 7** (right).

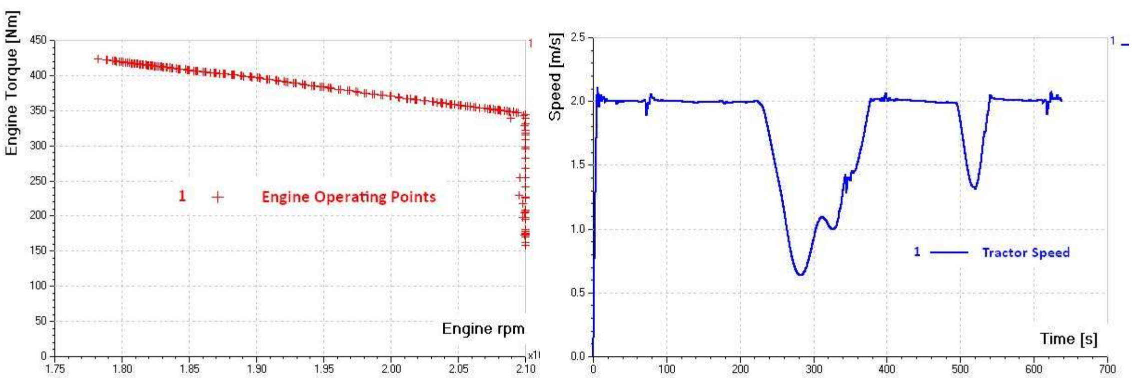

Figure 7. Engine Operating Points and Tractor Speed

Currently a static optimization in the Controller is realized. For that reason pursued goal is to optimize overall efficiency η. Mathematically, η can be expressed as follows.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{F_{Pull} \cdot v + T_{PTO} \cdot n_{PTO} + p_{WH} \cdot Q_{WH}}{P_{Fuel}}$$

P_{Fuel} is the chemical power of the fuel. In cycle Z7PR and realized operating strategy, characteristic of η along cycle Z7PR is shown in **Figure 8**.

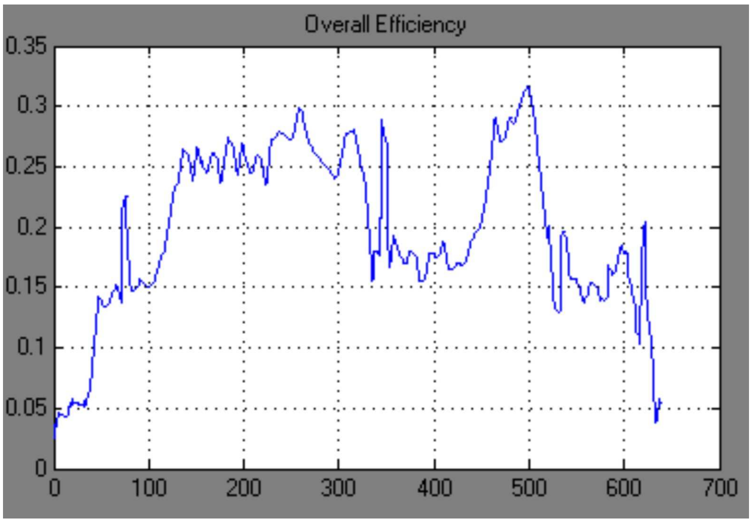

Figure 8. Overall efficiency over Time

It is remarkable that the overall efficiency is high when the total power is high. Otherwise low power demand at the beginning of the cycle leads to an overall efficiency of about 5%. One major reason is that engine runs at nominal rpm of 2100 and therefore high specific fuel consumption. In this case we use an engine with a maximal efficiency of 35,3 % at 1700 rpm. A high power consumption of the PTO leads to a high efficiency. Nevertheless maximal overall efficiency is about comparatively low 31%, due to a comparatively low engine efficiency.

According to Section 2, fuel consumption is entirely specified by vector $\vec{v}$ spanned by the power flow through the tractor interface $\vec{v}_S$ and internal adjustments $\vec{v}_A$. Consistently, clusters of a similar $\vec{v}$ lead to similar fuel consumption. From the definitions in Section 2, it is evident that no element of $\vec{v}_A$ may be completely described by elements of $\vec{v}_S$ and vice versa.

Therefore, redundancies in $\vec{v}_S$ and $\vec{v}_A$ must be dissolved. To achieve holistic optimization, redundancies need to be dissolved only in $\vec{v}_S$, as in this way the adjustment possibilities contained in $\vec{v}_A$ will not be reduced.

Internal adjustments in the tractor are:

$$\vec{v}_A = \begin{pmatrix} n_{Crank} \\ v \\ n_{PTO} \\ DC \\ GR \\ 4w \\ Q_{WH} \end{pmatrix}$$

| n_{Crank}= rpm crankshaft; v= velocity; n_{PTO}= rpm PTO; DC= differential clutch; GR= gear;4w= 4-wheel clutch; Q_{WH}= flow rate working hydraulic;

$\vec{v}_S$ characterizes the power flows across the interfaces of the tractor. A tractor has the following interfaces:

- Rear Coupling Device
- PTO
- Valve Working Hydraulic
- Wheel-soil Contact

Thus vector $\vec{v}_S$ is

$$\vec{v}_S = \begin{pmatrix} F_{pull} \\ T_{PTO} \\ p_{WH} \\ T_i \\ \sigma_i \end{pmatrix}$$

| F_{Pull}= pulling force; T_{PTO}= torque PTO; p_{WH}= pressure working hydraulic; T_i= torque wheel i; σ_i= rpm wheel i

In a first instance, in order to reduce dimensionality of $\vec{v}$, working hydraulics (WH) are neglected and a working cycle according to **Figure 9** is examined. In this cycle different working situations are simulated consecutively.

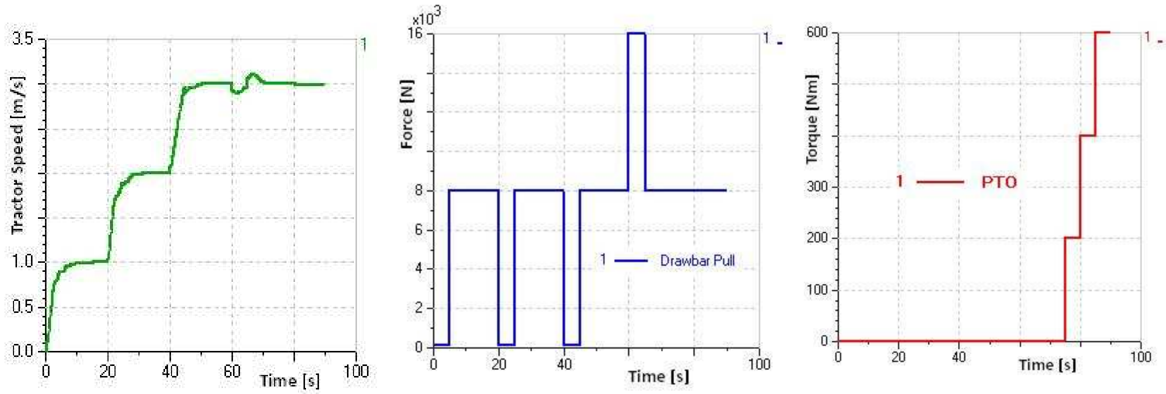

Figure 9. Examined Cycle

The task of the Observer in the applied O/C architecture is to characterize the current system state and report it to the Controller. The vector $\vec{v}$, as has been described above, constitutes the basis of this state characterization. To show, that the given entries in $\vec{v}_S$ and $\vec{v}_A$, are suitable to characterize the system state regarding fuel consumption, two conclusions have to be verified: first, while the tractor's working situation and interior degrees of freedom are not changing (in the simulation: while the model input is not changing), the vectors $\vec{v}$ must stay very similar, and second, similar vectors $\vec{v}$ must result in a similar fuel consumption b_e, as $\vec{v}$ is meant to characterize the system state regarding the target function b_e entirely. To show this, all vectors $\vec{v}$ that were gathered during the examined cycle (see **Figure 10**) were clustered using the *kmeans* clustering algorithm. Kmeans is an algorithm that summarizes points in a specific number of clusters in a way the norms between single points are minimal. This clustering shows that consecutive vectors during a constant situation are assigned to the same cluster. Subsequently, the resulting clusters have been compared to the measured efficiency of the tractor. **Figure 10** shows this comparison. The clusters where generated using kmeans with a value of 10 clusters. The figure shows a plot of the simulated system efficiency over time in simulation ticks at a sample rate of 33Hz. Additionally, the time slots, where consecutive vectors $\vec{v}$ have been assigned to the same cluster, are separated by vertical lines. The plot clearly shows the correlation between cluster formation and static system states, as well as the fact that vectors $\vec{v}$ within the same cluster result in a very similar system efficiency, and thus, fuel consumption.

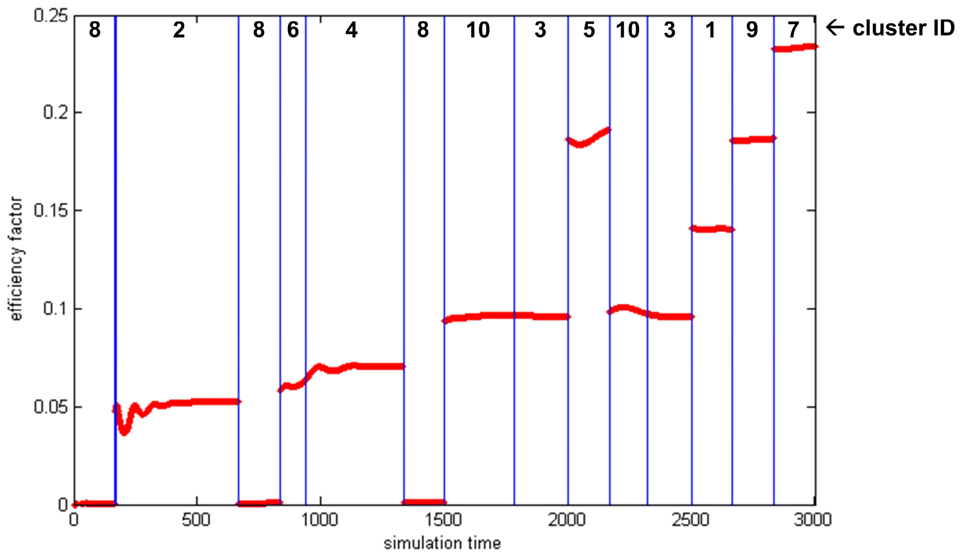

Figure 10. Plot of efficiency factor, compared to clusters of vector $\vec{v}$ (clustering by kmeans with k=10)

The results show that the efficiency within one single cluster of $\vec{v}$ is nearly the same. Although many more tests have been done, this example representatively indicates that vector $\vec{v}$ entirely describes the situation of the machine regarding the target function. Since $\vec{v}_A$ is already determined by the adjustment possibilities in a tractor, we found a $\vec{v}_S$ that is able to characterize the external situation.

6. SUMMARY AND FUTURE WORK

Developments in the area of mobile machines show a rising amount of degrees of freedom over the last decades, the basics for profound optimization. However conventional optimizations use static characteristics to control single degrees of freedom individually. Recent research studies show distinct potential of simultaneous optimization of several subsystems in a cross-linked mobile machine. Based on that, a notion of holistic optimization as a consequent continuation of mentioned research studies was given here. The O/C architecture is capable of accomplishing holistic optimization. In this exposé the operating strategy is a clustering based holistic static optimization. The optimized operating strategy is the result of several online loops, which assign an optimal action (part of an action map) to a set of possible situations. In contrast to conventional management systems the holistic approach involves all machine components simultaneously. Currently a simulation model of the demonstrator, a tractor, was build to design and test single modules of the Observer and Controller. First results of the tractor model and MiL-simulation were presented. One important result is the determined vector $\vec{v}$ that entirely describes the situation regarding the target function and therefore is the basis for holistic optimization.

Future work will focus on enhancements of the modules. Currently system states are considered purely statically. In the case of clustering, correct sensitivity quantities need to be set to precisely distinguish between different influences of single influences on fuel consumption. Furthermore dimensionality of $\vec{v}_S$ is very high. To get proper solutions $\vec{v}_S$ needs to be reduced. One possibility is to integrate several dimensions to a new one, while at the same time not changing the output significantly.

Afterwards the architecture will be implemented into the real tractor according to the methods suggested by the V-Model using RCP Hardware. Additional measurement instrumentations needs to be applied and the communication between tractor and RCP hardware must be established. Here a so called CAN-Gateway will be used to translate information of the tractor CAN-Bus system to the exterior Bus system. Practical operating tests in the field need to prove fitness under real conditions. Their evaluation additionally serves as validation data for the tractor model and again to advance single modules in the O/C architecture. Therefore, this process is to be considered iteratively.

Another interesting aspect is that the architecture offers the possibility to set different optimization preferences by an external operator. A sole optimization of fuel consumption is in many cases unrequested. Instead the operator has many goals like optimization of output power per acreage or emissions in case of legislation restrictions. Since these goals generally compete with each other, they need to be combined to a multi criteria optimization problem. Goal is to provide an interface for the driver to gain the possibility to individually set preferences for this multi criteria optimization problem.

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