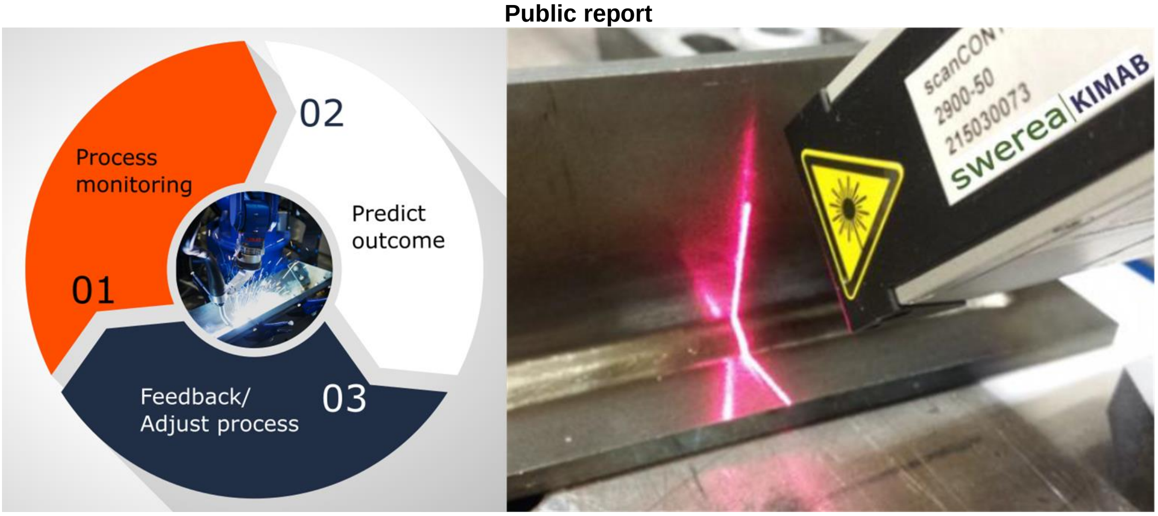
PREMOD

Predictive models and machine learning algorithms as a step to towards adaptive weld process control – A pre-study

Public report



Project within FFI Machine Learning
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FFI Fordonsstrategisk Forskning och Innovation

Content

1. Summary

The project investigated how a combination of predictive models and machine learning algorithms could be used to increase the robustness and flexibility of robotic welding operation by a systematic approach in order to understand and utilize more control parameters in the overall welding system than what is normally done today. Robotized welding can be seen as an open dynamic system, containing a lot of control and noise factors with known and unknown effect. It also contains many hidden interactions, which makes it is extremely tricky to set up. Particularly, since it needs to meet several quality characteristics simultaneously. However, by controlling additional factors, such as the welding geometry, including torch orientation relative the part position as well as the weld beam parameters it is possible to both set-up a particular welding operation to be more robust (i.e. to be insensitive to incoming part-to-part variations) when possible and/or make it adjust for incoming variation when overall robust setting do not exist. The former part requires a multi-parameter predictive modelling technique based on efficient off-line experimentation and the latter requires a dynamic on-line control that can adjust welding angles based on the incoming variation of critical factors, such as a varying gap between steel plates after fixturing and tack welding.

The overall aim was to increase productivity, improve quality and to reduce cost of inspection, that is, to reduce the need for scrapping, rework and overproduction by achieving an optimal weld quality independent on incoming geometrical deviations in the part to be welded. The long-term scope for this development is to introduce and potentially exceed the “adaptive” control that a skilled welder can accomplish but in a robotized welding process. This combines the best of both worlds, adaptive control of a manual welder and stability and repeatability of robotized welding.

Input and output parameters was measured and documented using a novel, newly developed measurement system described in more detail in the background section. This measurement system was utilized to scan weld quality after welding as well as incoming part variations in the fixturing step prior to welding to generate important input data for modelling purposes.

The pre-study will focus on laying the groundwork for this long-term vision by reaching the following objectives:

- Establish relevant input and output parameters of major effect on the robustness of the welding process and the resulting weld quality.
- Demonstrate existing technologies for on-line measurement of relevant input and output parameters related to robotic welding as well as deliver a plan for future work where new developments are needed.
- Produce a simplified model with the potential to adaptively control the robotic weld process
- Investigate suitable ML algorithms to use in combination with a statistical approach to achieve adaptation/self-learning of the final model.

The pre-study successfully demonstrated an effective predictive modelling approach that related welding system settings such as travel speed, wire feed rate and the welding torch orientation in relation to the work piece to multiple weld quality aspects such as penetration depth, throat thickness, weld toe radii, excessive filler material usage etc.

The main intention of the pre-study was to utilize these models to develop a fully automated welding system where robot and power source makes decisions on how to weld based on incoming part variations but it was also concluded, already in the application for the pre-study project, that a full demonstration of an automated welding system was not possible in a smaller pre-study.

Instead, the PREMOD pre-study project collaborated with students from Chalmers University and Penn-State University to demonstrate how a robot can alter its angles relative to an object based on external sensor and model input. These results were published in a bachelor thesis [1] made possible through a collaboration financed by Volvo Construction Equipment, who was also a partner in this pre-study.

The students demonstrated adaptive robot movement based on output from regression models developed according to the methodology utilized in the PREMOD pre-study.

PREMOD also demonstrated the use of novel sensors to gather data for modelling. In this task several new research needs were identified, both regarding algorithm development for data processing but also in database development and data management for large scale use of quality data in future applications / research.

Machine learning algorithms were discussed thoroughly throughout the pre-study project. After defining the scope and limitations of the project vision regarding a fully adaptive welding system, several potential tasks for machine learning were identified.

Possible Tasks:

- Data preprocessing, including dimensionality reduction, outlier detection, feature selection etc.
- Model selection and model training using the input-output time series including hyperparameter optimization, validation etc.
- Model evaluations such as prediction performance, prediction certainty etc.
- Detection of anomalies and changes in input data or in the input-output data relation

Several additional research needs were identified in this pre-study project and divided into four main topics; Design of Experiments and predictive modelling, machine learning, data gathering and hardware and communications.

2. Sammanfattning på svenska

Projektet har studerat hur en kombination av prediktiva modeller och maskininlärningsalgoritmer kan användas för att förbättra robusthet och flexibilitet i robotsvetsapplikationer och således öka förståelsen för hur inställningsparametrar samverkar samt möjliggöra utnyttjandet av fler inställningsparameterar än vad man normal använder vid optimering av ett komplett svetssystem, inkluderat såväl svetsmaskin som robot.
Robotsvetsning kan liknas vid ett dynamiskt system bestående av många olika styr- och brusvariabler med både delvis kända och okända effekter. Systemet innehåller även många okända samverkanseffekter mellan styrvariabler vilket gör det väldigt svårt att på ett kontrollerat sätt optimera och ställa in systemet. Speciellt svårt blir det då det oftast är krav på att flera kvalitetsmått ska uppnås samtidigt.
Genom att kontrollera flera variabler samtidigt, så som svetsvinklar samt traditionella variabler kopplade till svetsutrustningen, är det möjligt att erhålla en mer robust svetsprocess (tålighet mot variationer mellan komponeter) eller kontinuerligt justera svetsprocessen baserat på inkommande variation när en generell, övergripande robust inställning inte är möjlig att hitta. Det förstnämnda kräver en multivariat prediktiv modelleringsteknik baserad på effektiva off-line-experiment och det sistnämnda kräver en dynamisk online-kontroll som justerar svetsvinklar och svetsparametrar baserat på kritiska parametrar i den inkommande variationen så som varierande gap mellan plåtar efter fixturering och häftsvetsning.

Det huvudsakliga målet med projektet var att öka produktivitet, förbättra kvalitet och reducera kostnad för övervakning av en svetsprocess d.v.s. att minska behovet av skrotning, omarbetning och överproduktion genom att åstadkomma en optimal svetskvalitet oberoende av inkommande geometriska variationer av komponenterna som ska svetsas. Det långsiktiga målet med denna utveckling är att introducera en adaptiv styrning i en robotsvetsprocess som är lika bra, eller bättre än den förmåga som en erfaren svetsare besitter. Detta kombinerar både en svetsares förmåga att finjustera efter behov samt en robots noggrannhet och repeterbarhet.

Input- och outputparametrar mättes upp och dokumenterades med ett nyutvecklat mätsystem som beskrivs i mer detalj under bakgrundskapitlet i rapporten. Mätsystemet användes för att scanna svetskvalitet efter svetsning samt inkommande komponenters geometriska variation efter fixturering, före svetsning, för att samla in nödvändig data till efterföljande modellbygge.

Förstudien fokuserade på att lägga grunden för den långsiktiga visionen genom att möta följande mål:

- Etablera vilka input och output parametrar som har en stor effekt på robusthet av svetsprocessen och den resulterande svetskvaliteten.
- Demonstrera existerande teknologier för onlinemätning av relevanta input och output parameterar kopplat till robotsvetsning samt leverera en plan för vilken framtida utveckling som är nödvändig för att nå projektets långsiktiga vision.
- Utveckla en förenklad modell med potential att adaptivt styra en robotsvetsprocess
- Utvärdera möjliga maskininlärningsalgoritmer som kan användas tillsammans med statistisk modellering och prediktiva modeller för att åstadkomma en självlärande och anpassningsbar slutgiltig modell.

Inom ramen för förstudieprojektet demonstrerades en effektiv metodik för prediktiv modellering som relaterar flertalet inställningsparameterar från svetssystemet, så som svetshastighet, vinklar mellan svetspistol och objekt samt trådmatning, till ett antal svetskvalitetsmått som penetrationsdjup, storlek på svets (a-mått), övergångsradie mellan svets och plåt, hur effektivt det tillsatta materialet bidrar till svetsens storlek med mera.

Den huvudsakliga intentionen med resultaten från förstudieprojektet var att utnyttja de framtagna modellerna, och metodiken för framtagandet av dem, till att åstadkomma ett fullt automatiserat svetssystem. Ett system där robot och svetsströmkälla tar beslut om hur de ska ställa in sig och uppnå optimalt resultat baserat på externa sensorsignaler som avspeglar inkommande materials variation i geometri. Det var dock, redan vid ansökningstillfället, konstaterat att en fullständig demonstration av ett automatiserat svetssystem inte var möjlig att uppnå inom ramen för denna begränsade förstudien.

Istället samverkade denna förstudie med studenter från Chalmers och Penn-state universiteten för att demonstrera hur en robot kan justera sina vinklar i förhållande till ett objekt baserat på input från externa sensorer och modeller. Resultaten från studentarbetet publicerades i en kandidatexamensrapport [1] och hela studentarbetet finansierades av Volvo Construction Equipment som också deltog som part i denna förstudie. Studenterna demonstrerade en robot som adaptivt justerade sin bana baserad på input från regressionsmodeller som var framtagna baserat på samma metodik som den som använts inom detta förstudieprojekt.

Inom ramen för förstudieprojektet demonstrerades även hur nyutvecklade sensorer och mjukvara kan användas för att på ett tidseffektivt och noggrant sätt samla in kvalitetsdata, både före och efter svetsning, som input till modellering. I detta arbete identifierades flera nya forsknings- och utvecklingsbehov, bl.a. fortsatt förfinande av algoritmer för databearbetning samt behovet av en databasstruktur för hantering och av de datamängder som genereras så att dessa finns lättillgängliga för framtida forskningsprojekt.

Maskininlärningalgoritmer och metoder diskuterades grundligt genom hela förstudieprojektet. Efter att förstudiens omfattning och begränsningar hade definierats i relation till visionen kring ett fullt adaptivt svetssystem så identifierades ett antal möjliga användningsområden för maskininlärning.

Några områden skulle kunna vara:

- Databehandling, inkluderat reducering av dimensioner, extremvärdesdetektion osv.
- Val av modell och träning av modell
- Utvärdering av modell så som prediktionssäkerhet
- Detektering av förändringar i inputdata och relation mellan input och output data.

Ett flertal framtida forskningsbehov har identifierats i förstudieprojektet och delats in inom fyra huvudsakliga områden; statistisk försöksplanering och prediktiv modellering, maskininlärning, data insamling samt hårdvarukommunikation.

3. Background

This project addresses production issues that arise during welding of components where incoming variations differ between parts. Gaps between sheets vary in size and the angle between sheets also differs. With increased use of high strength steels and more complex geometries in welded structures it becomes more and more difficult to ensure perfect fitting of parts prior to welding. Processes like bending and cutting also becomes more complex with increasing strength of the base materials used which makes fitting of parts and reaching the final manufacturing tolerances more difficult. Geometrical variations on incoming parts can thus lead to large deviation in weld quality and scrapping of parts, rework and overproduction as a result. Seam tracking equipment exists and simple tactile versions are in use at most production sites but these systems mostly adjust the Tool Center Point (TCP) of the welding gun and do not adapt the welding process based on other geometrical aspects.

To minimize the need for scrapping and rework, large safety margins are applied to the welds but this in turn leads to overproduction for parts that are within normal manufacturing tolerances. There is much to gain with a welding process that could adapt based on incoming part variation and achieve optimal weld result. With the uncertainty of incoming part variations, it is difficult to ensure weld quality at sensitive locations in the welded structure and this is an essential part for enabling stronger and more light-weight materials, such as ultra-high strength steels, in the heavy vehicle industry.

In a previous Vinnova project (ONWELD, 2013-04696) an automated weld quality measurement system was developed [2], Figure 1. This system registers all necessary weld quality parameters that are possible to determine trough visual inspection / inspection from the outside as well as incoming part tolerances such as gap, insufficient bending angles and so forth. Large amount of data is generated that describes the exact weld quality produced at any moment in time for a fixed set of incoming part tolerances. This type and amount of data have previously not been available and the idea of this project is to feed this ever-growing dataset into a combination of predictive models and machine learning algorithms to build an adaptive control system for MIG/MAG welding processes. This measurement system will be utilized to scan weld quality after welding as well as incoming part variations in the fixturing step prior to welding.

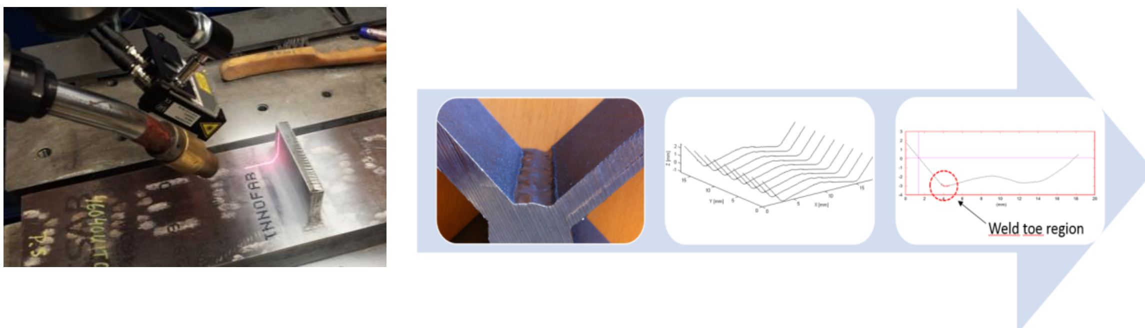


Figure 1 - Illustration of the automated weld quality measurement system

The merging of Lean and Six Sigma during the recent years has advanced the continuous improvement methodologies towards a customer-based operational development approach which opens for how product quality improvements can be balanced with operational efficiency development. Welding operations face the same challenge: output weld strength requirements need to be fulfilled and welding operations productivity need to be maintained and developed. For example, it is crucial to maximize the transition radius between the base plates and weld bead to avoid stress concentrations that accelerate fatigue crack initiation and at the same time maximize weld penetration depth while keeping the bead thickness on target. It is a complex multi-parameter optimization problem with several trade-offs which the existing control system do not address. In short, we are not utilizing the multi-axis robotized welding systems to its fullest potential to meet the customer-based operation development challenge: improved quality and productivity simultaneously.

Existing tools utilized in the industry for MIG/MAG welding consist of various configurations for seam tracking to ensure that the weld is made at the right place on a component. Seam tracking systems are a digital aid for the robot to adjust its position based on variations in the joint configuration. However, the seam tracking systems only alter the robot TCP to keep the process on target, see Figure 2.

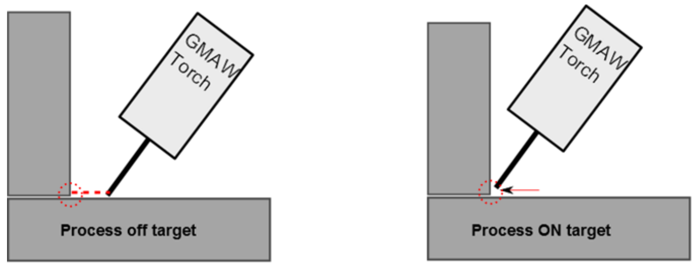


Figure 2 – Illustration of a seam tracking system altering robot TCP.

There are also a few systems that combine both seam tracking and some type of adjustment of welding parameters. Examples of such systems are iCAM from IGM [3] and POWER-TRAC [4] from ServoRobot where a traditional laser based seam tracking system has been further developed to estimate required weld volume and adjust welding speed and wire feed rate accordingly. These systems are available on the market and state-of-the-art today. They do however not address the overall problem to completely fulfil design specifications of toe radii, penetration and bead thickness all at once.

In academia MIG/MAG weld quality is a relatively hot topic focused on different techniques to determine the weld quality as well as different means of controlling robot movement to improve weld quality. Methods that are utilized are different types of vision systems, thermography, acoustic emission etc. to determine the weld quality. In an article by A. Kuss et.al. [5] a relationship between gap size and throat thickness is developed and used for adaptive control of the MAG welding process. Studies by M. Ebert-Spiegel et.al [6] demonstrated a different model utilized for gap bridging taking both wire feed rate and welding speed into account. In this study, it was suggested to further explore and implement the influence of torch angles relative to the plate and welding direction to achieve an improved model.

Artificial intelligence methods, in particular machine learning (ML), are becoming mature and are being used to solve industrial problems in all areas. In the domain of welding, Günther et al [7] describe work on using ML for laser welding process control; other ML applications in the welding area have e.g. explored acoustic sensor signals to assess quality [8]. In contrast to domain models laboriously built on deep domain knowledge, machine learning models are data driven and can learn important relationships of the process from recorded data. They can learn to model complex, hard to specify relationships. On the other hand, they often require large amounts of data and can only learn to make sensible predictions within the range of the data used to train the model. By combining the two approaches, better accuracy than with a purely data driven model can be achieved, with less effort than with a model based purely on first principles.

Previous studies [9] showed that many other parameters than wire feed rate and welding speed influence the output weld geometry. Torch angles, plate orientation towards gravity and welding position have shown to be of outmost importance for the resulting weld geometry. For example, the gap between plates in Figure 1 strongly influence both weld radius and penetration. It has been shown that when the gap is zero the optimal welding position to maximize toe radii is to push the weld downhill and when the gap is 2 mm the optimal welding position is to pull the weld uphill, that is to have the welding gun in front of the weld pool in the welding direction. To control an even gap with fixtures prior to welding for large structural components is difficult, since there are many variation sources that influence gap variation. To solve this problem one opportunity is to measure incoming part variations prior to welding as well as the output weld geometry after welding. Through the use of this data, models can be developed to dynamically predict the optimal welding angles of plates and gun as well as welding parameters during welding to get a robust bead geometry mitigating the incoming gap variation. So far there is no comprehensive study taking all parameters into account.

4. Purpose, research questions and method

Welding is complex and variation in inputs and from noise factors makes it extremely difficult to set-up robotized welding cells. The theme of this work is to elevate the understanding of how to set-up and operate automated welding in order to increase its robustness. The problem is that current welding systems consist of several autonomic sub-systems that are controlled from a technical point of view – but not from a customer requirement point of view. For example, sub-systems exist that control a stable welding arc, but no system exist to keep the outgoing weld geometry on target. It is today mainly controlled by manual post-processing quality assessment and incremental manual set-up adjustments. It makes welding operation costly to set-up and in-flexible to input variations, such as alternative suppliers and/or changes of raw material. It is not known today how to structure and standardize the set-up and operation procedures in order to utilize the robotized welding systems to their full-potential relative their individual configurations. By that assuming that a grand overall optimal setting for robotized do not exist and each individual welding system need to set-up and operated individually in order to determine and understand what opportunities and trade-offs that limits their individual process windows. This is particularly limited today by the understanding of how the sub-systems interact and communicate.

The research questions addressed are:

1. **Can the welding setup parameters be predicted and automated to adjust for incoming variation in steel plate fixturing in order to keep outgoing weld quality on target, based on an off-line predictive modelling of a range of the most important and known control factors?**

2. **Can the controlling off-line models in (1) dynamically be up-dated using ML monitoring other factors of the welding environment and its inputs**

The methods in 1 is to experimentally verify the utilization of predictive modelling for welding geometry control off-line and to develop and test a concept for torch angle control. The method in 2 is to theoretically explore the existing preconditions, methods and limitations for data collection and analysis in order to potentially up-date the welding geometry controller dynamically.
The contribution from this work is a potential novel strategy and workorder procedures as well as point out sub-system development needs.

5. Objective

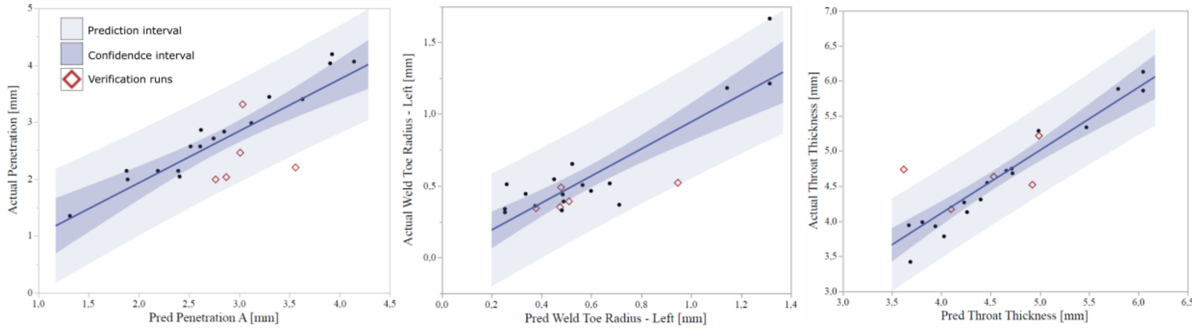
The vision of the pre-study is to demonstrate how predictive models and machine learning algorithms can be used to alter torch orientation, weld process parameters and robot path to adapt the joining process based on incoming part-to-part variations. The overall aim is to reduce the need for scrapping, rework and overproduction by achieving an optimal weld quality independent on incoming geometrical deviations in the part to be welded. The long-term scope for this development is to introduce and potentially exceed the “adaptive” control that a skilled welder can accomplish but in a robotized welding process. This combines the best of both worlds, adaptive control of a manual welder and stability and repeatability of robotized welding.

The pre-study will focus on laying the groundwork for this long-term vision by reaching the following objectives:

- Establish relevant input and output parameters of major effect on the robustness of the welding process and the resulting weld quality.
- Demonstrate existing technologies for on-line measurement of relevant input and output parameters related to robotic welding as well as deliver a plan for future work where new developments are needed.
- Produce a simplified model with the potential to adaptively control the robotic weld process.
- Investigate suitable ML algorithms to use in combination with a statistical approach to achieve adaptation/self-learning of the final model.

6. Results and deliverables

The overall result of the pre-study is a novel strategy and methodology for welding operation set-up and development, consisting of work-order procedure and supporting technical concepts for monitoring and control. The pre-study successfully demonstrated the use of effective predictive modelling techniques for multi-parameter system exploration based on design of experiments (DoE) that utilizes a wider range of welding system settings such as travel speed, wire feed rate and the welding torch orientation in relation to the work piece in order to fulfil requirements on several weld quality characteristics simultaneously such as: penetration depth, throat thickness, weld toe radii and excessive filler material usage. The graphs below represent examples of regression models developed in the pre-study project. Red diamonds represent verification runs that are not included in the making of the regression model.



The main intention of the pre-study was to utilize these models to develop a fully automated welding system where robot and power source makes decisions on how to weld based on incoming part variations but it was also concluded, already in the application for the pre-study project, that a full demonstration of an automated welding system was not possible in a smaller pre-study.

Instead, the PREMOD pre-study project collaborated with students from Chalmers University and Penn-State University to demonstrate how a robot can alter its angles relative to an object based on external sensor and model input. These results were published in a bachelor thesis [1] project financed by Volvo Construction Equipment, who was also a partner in is pre-study.

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Machine learning algorithms were discussed thoroughly throughout the pre-study project. After defining the scope and limitations of the project vision regarding a fully adaptive welding system, several potential tasks for machine learning was identified.

Possible Tasks:

- Data preprocessing, including dimensionality reduction, outlier detection, feature selection etc.
- Model selection and model training using the input-output time series including hyperparameter optimization, validation etc.
- Model evaluations such as prediction performance, prediction certainty etc.
- Detection of anomalies and changes in input data or in the input-output data relation

Later a literature study was performed to identify the most suitable machine learning methods, their strengths and weaknesses and their applicability for the identified tasks. It was also concluded that to actually apply the machine learning methods, a more realistic case of data generation was needed and this is only possible to achieve in a future, larger research project.

Several additional research needs were identified in this pre-study project and divided into four main topics; Design of experiments and modelling, machine learning, data gathering and hardware and communications.

Compared to the deliverables defined in the application all deliverables were fulfilled. In relation to the goals and deliverables of the FFI program this pre-study project have laid the ground work for many future potential contributions to the FFI targets and most importantly inspired the industry to continue development within advanced adaptive welding systems in future research projects. The pre-study in itself was not designed to solve all issues related to adaptive weld control and can thus not be expected to deliver results that directly contribute to FFI targets on a short term. The vision and plan forward for this research is however on target for the FFI programs.

In the road map for FFI the overall aims are to strengthen the global competitiveness of the Swedish industry, minimized environmental impact and increased vehicle safety. This project mainly addresses the goal of increased competitiveness and reduced environmental impact through the development of more flexible manufacturing solutions that enables effective use of resources, improved productivity, optimized performance relative several requirements and life cycle footprint. It also enables a more sustainable manufacturing by reducing scrapping, rework and overproduction.

The vision of this project mainly connects to the following focus areas within the FFI – Machine learning program:

- **Verification and validation of solutions based on ML-algorithms** laying the ground work for data mining of both input and output variables of the MIG/MAG welding process and creating a basic concept for a combined predictive and self-learning model utilized for adaptive control of a robotized welding process.

- **Robust optimization/control of production systems:** Through the use of a combination of predictive models and machine learning algorithms lay the ground work for a model with the means to improve quality and flexibility of the welding process without demanding higher precision and tighter tolerances of the inputs.

As stated in the program description machine learning should be viewed in a broad perspective that can be applied widely in any of the FFI-program areas. This project in particular is closely related to the FFI-program Sustainable Production. Main contributions to the targets of Sustainable Production can be summaries as:

- **New products with high life cycle efficiency:** By utilizing an adaptive weld process control system, welded joints can more readily be optimized for different requirements at different locations in a welded structure. This will lead to resource efficient production with lower requirements at less significant areas of the structure and improved life cycle efficiency for the end product by optimizing weld quality for improved fatigue life at highly loaded areas.

- **Improved quality and reduced weight**: by securing high-quality weldments the introduction of more weight-to-strength efficient materials is facilitated resulting in reduced weight in welded structures.

- **Reduced environmental impact**: increase transport productivity in terms of handled ton/hour and thereby reducing CO_2 emissions.

- **Flexibility, resource efficiency and minimization of emissions from the manufacturing**: New design possibilities enabling less filler material usage, differentiated requirements and narrower safety margins. An adaptive weld process can adapt and deliver optimal results even with a large part-to-part deviation in tolerances resulting in a reduced need for scrapping, rework and overproduction.

- **Increased process control and reduced lead-time**: Adaptive weld process control will reduce overproduction, rework and energy consumption. An adaptive welding process can also reduce lead time for introduction of new parts in the manufacturing process.

- **Increased international competitiveness**: Products with better and more controlled performance.

7. Dissemination and publications

Results from the pre-study have been actively shared within the participating companies. A plan for at least two different continuation projects has been developed and activities are on-going regarding involvement of additional companies in future research projects. Results are thus being presented to additional companies, out-side of the original consortia.

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	This pre-study is engaged in a research topic that is not widely explored within the welding community, at least not in the industry. This pre-study have definitely inspired the industry to take new measures in the development of automated welding systems and implementation and utilization of new, novel sensors for quality assurance.
Be passed on to other advanced technological development projects	X	Two new spinoff projects are under development and new project partners are being involved.
Be passed on to product development projects	X	Some of the industrial partners in the project have an intent to include some of the development in this and future research projects in their offers. Winteria, an SME in the field of weld quality assurance and related systems, is one of them. ESAB might also have an interest as a supplier of welding hardware and consumables.
Introduced on the market		Nothing has been introduced on the market as of now. It is however not unlikely that products based on this and future development will reach the market.
Used in investigations / regulatory / licensing / political decisions		

7.2 Publications

The pre-study project has collaborated with students at Chalmers and Penn-State University to demonstrate how a robot can be adaptively controlled based on external sensor input. Results have been published in a thesis report made by the students [1].

8. Conclusions and future research

Conclusions:

- Predictive modelling of out-going weld quality aspects is possible
- Prediction of penetration depth based on outer weld geometry is plausible
- Both welding power source settings and robot angles have great influence on resulting weld quality and can be optimized simultaneously in a multi-objective optimization
- Additional development is needed to implement the develop methodology in future industry applications such as:
    - Fully adaptive weld system
    - Utilize advanced methodologies for robust and optimized development of welding procedure specifications (WPS)

Future research:

During the course of this pre-study several important research questions for a potential continuation project were noticed. Additionally the participating companies became divided regarding a potential scope and content of a continuation project. Industrial companies that perform welding, utilizes welding in their manufacturing operations or support customers within welding agreed that the original scope of a complete adaptive system is still very interesting but perhaps too far from the current developments being made within each company. Instead they would like to focus on how the predictive models developed demonstrated in this pre-study can be utilized in a methodology to create robust welding procedure specifications (WPS) for certain situations. System manufacturers (welding equipment and robots) also find this scope interesting but would still like to focus on achieving a fully adaptive weld system based on predictive models and machine learning. Because of these divagating interests the continuation of the PREMOD pre-study project was decided to be split into two applications:

- **Project 1: Predictive modelling as a methodology for robust and resource efficient WPS development**

- **Project 2: Predictive modelling and machine learning as means for fully adaptive control of the MAG-welding process**

9. Participating parties and contact persons

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