

DATLAS

Data-Interactive Process Monitoring for Laser Welding

1. Relevance of the Project

1.1 Introduction to the subject

Among all joining techniques laser welding is a high potential/high risk technology. In particular it is an *enabler technology*, enabling joint design and material combinations not possible with other techniques – thus enabling highly advanced products. Laser welding can lead to superior features like high quality (precision, strength, etc.) and high speed but often suffers from the high investment costs and from the sensible welding process bearing a high risk of failure if not applied properly. Welding defects (e.g. pores, cracks, holes, undercut, stress raisers, cold laps, lack of penetration or bridging failure) can take place that lead to unacceptable mechanical properties of the product. While the optimum process parameters are found through systematic experiments and experience, the application in an industrial production environment bears the risk of fading away from these optimum parameters. Measures to handle this fading are either the exploration of a large robust process window, or process monitoring for on-line detection of failure (ideally followed by process control to automatically avoid/repair the defect). In terms of sensors for laser welding it can be distinguished between seam tracking, height control, in situ process monitoring and control, and post process inspection. DATLAS focuses on in situ process monitoring, but also aims at its suitable cooperation with the other sensors, and is an enabler for process control.

Process monitoring systems for laser materials processing (based on photodiodes) see Fig. 1(a) (here for laser cutting, developed by the applicant), are commercially available for many years. Their principle is based on empirically finding correlations (through experiments and experience) between the sensor signal (level, transients) and defects, Fig. 1(b) - in order to state a criterion for automated identification of such signal characteristics enabling automated defect detection in production. In welding the transients in the plasma and melt provide such information.

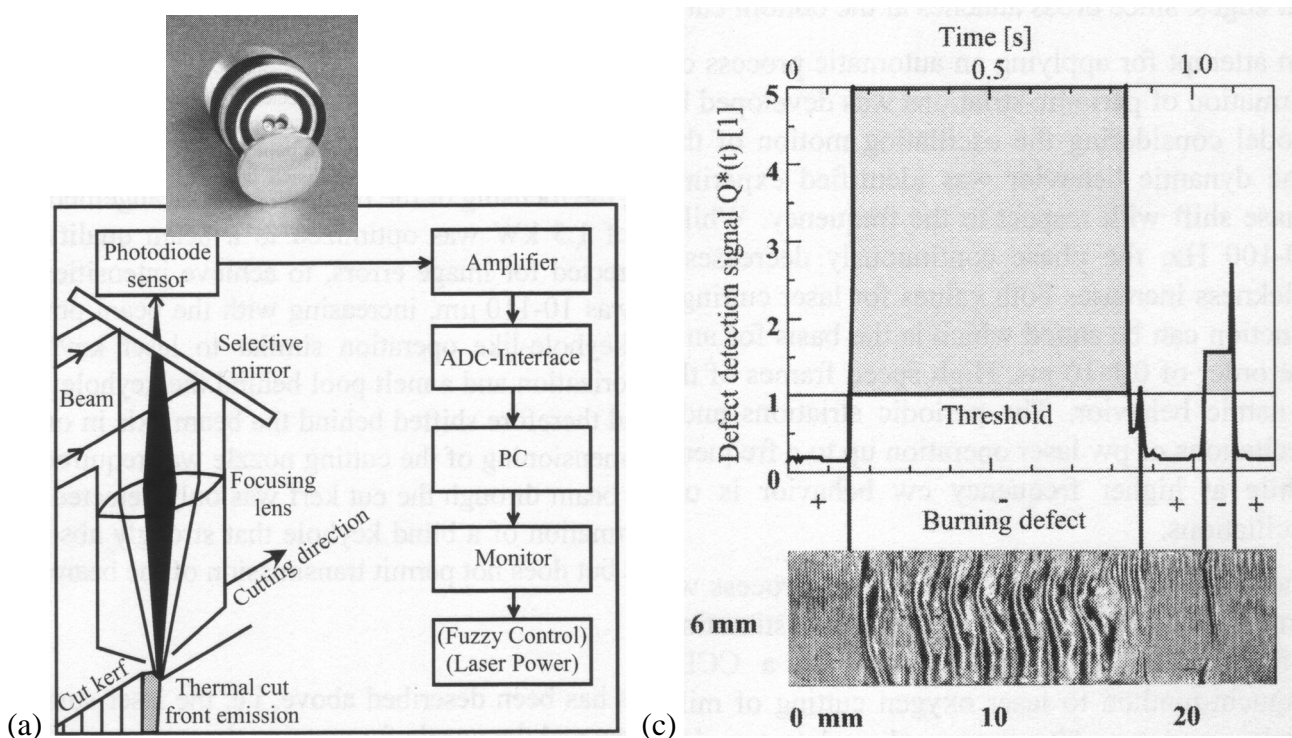


Fig. 1: Typical process monitoring system for laser processing (here: laser cutting): (a) system set-up with optical sensor detecting (b) quality defects (here: burning) through signal correlation

1.2 Weaknesses and needs

Most welding applications individually differ from each other (in terms of joint configurations, materials, laser systems or process parameters) and in turn their thermal radiation measured by the sensor. For today’s monitoring applications neither a common documentation nor generally applicable monitoring criteria exist. Therefore a new correlation criterion has to be identified for each new application. Despite a few basic guidelines and perhaps references to similar cases, the user has no systematic and safe method for finding a correlation, which even bears the risk of failing at all (or requiring long-time test runs) in applying an already purchased monitoring system.

The industry has a strong need for a systematic method safely and quickly leading to signal-defect correlations, moreover for higher reliability of the correlations. (Often failures are not detected or in contrast the production is interrupted due to wrong alert) Eventually the dream scenario is 100% reliable detection of any failure, which permits to eliminate expensive post-inspection. Purely empirical treatment is unsatisfactory. Instead, understanding of the physical context between the welding process and the signal is desired - for confidence and control.

1.3 Result of the project

The deliverable of the project will be a virtual support tool for monitoring of laser welding that will:

- (i) contain a comprehensive, systematic catalogue of defect-signal correlation cases,
- (ii) provide high level explanations on the context between the process and the signal,
- (iii) enable improvement of commercial process monitoring systems individually for each customer in a generic manner,
- (iv) store and analyse monitoring data to trace process fading and product failures.

Although generally applicable, the DATLAS-tool will be matched to the 4 participating end-users and to the 3 system suppliers. The experimental case analysis method will be generally applicable. The scientific results (expected to contain highly valuable novelty) will be published in journals.

1.4 Potential

Figure 2 illustrates the estimated potential released through DATLAS.

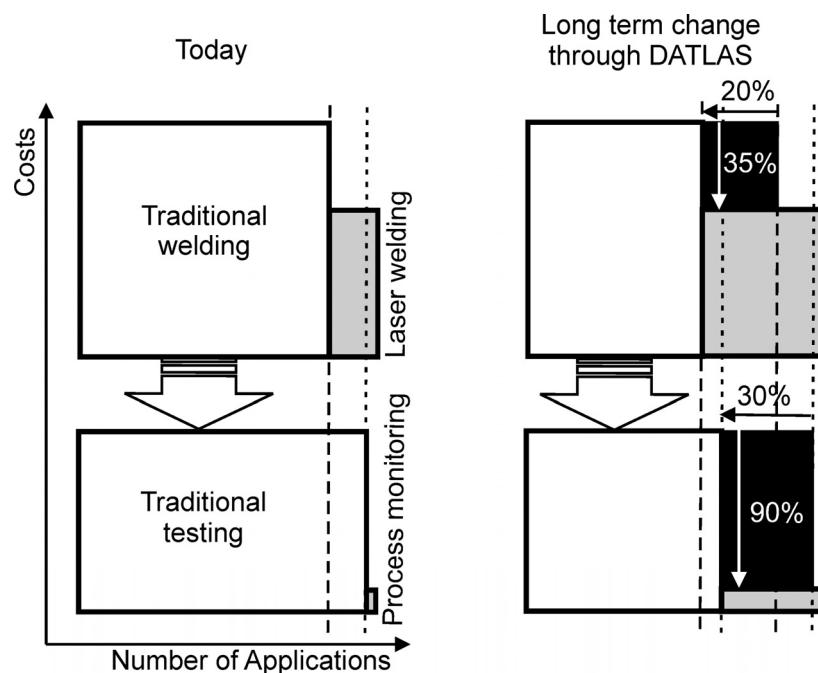


Fig. 2: Estimated scenario for a change through the project towards replacing expensive post-weld quality inspection by safe on-line process monitoring and in turn increase unprofitable laser welding applications

The total/average impact through DATLAS is estimated as follows (perspective: 10 years):

- On-line monitoring lowers the high traditional inspection costs to 10%
- Today 5 % of all laser welding applications apply monitoring, then 80%
- Thus the inspection costs of all laser welding applications today are reduced to 10%
- Additional 20% laser welding applications become profitable and will be launched

Today process monitoring and control of laser welding is far from its potential (=applied to all sensitive applications, 100% reliable). In turn laser welding is far from its potential use, along with the potential of product development enabled through laser welding.

The corresponding potential of DATLAS is manifold.

Primary the end-users of laser welding participating in DATLAS will directly benefit from improved knowledge on their process through their case study which is expected to significantly improve or to introduce process monitoring for their production, in turn leading to higher productivity (due to less post-inspection required and less on-line monitoring failures).

Secondly, the system suppliers can introduce the virtual support tool to their product range, leading to enhanced business and reputation for them. In particular it will lead end-users (with a knowledge advantage for Sweden) of laser welding to (i) introduction or (ii) improvement of process monitoring for laser welding or even (iii) to the implementation of laser welding (as becoming more profitable) and in turn to the reduction of post-inspection and machine-stop.

Thirdly, although not part of the project, DATLAS can even lead to automatic process control, thus to the reduction (rather than detection) of the number of failed products.

One possible scenario is shown in Fig. 2, illustrating that cost intense post-inspection can be reduced for many more laser applications and that new profitable laser applications can even be implemented. Today the investment costs are the main barrier for many potential laser applications.

In addition implementation of process monitoring leads to a higher degree of automation and of data handling, thus electronic recording of product and production will easily provide a better traceability for long term process behaviour (for maintenance, service) and for product failure tracing, even backwards.

The dimension of DATLAS basically encompasses all today's and future laser welding applications in Sweden (knowledge and lead time advantage) and worldwide (potential for the Swedish system suppliers). Moreover, the method can be transferred to monitoring of all other laser techniques (cutting, rapid prototyping, etc.). When finished the project immediately addresses the about 100 welding lasers installed in Sweden today, but in a mid and long term perspective all potential future laser applications, with a clear knowledge advantage for Sweden. E.g. there is no doubt in the automotive industry for massive application of laser welding in long term (increasing requirements for product and production flexibility and for quality, lower laser investment costs). E.g. Volvo CC, with only 12 high power lasers in production today, but more than 1000 resistance spot welding systems, gradually tends towards joining solely with laser and adhesive bonding. Today Saab and Scania have only one welding laser in operation each, but are aware about this global trend (requiring high investment). The rapid development of diode lasers lowers the investment barrier.

1.5 Relevance to the objectives of the programme

DATLAS addresses the two general objectives of the VINNOVA programme KSP as follows:

1) For the first time process monitoring of laser welding is treated on a deeply scientific knowledge level rather than empirically. This can enhance the profitability of virtually all Swedish laser welding applications (and their products) today (100) or in the future (growth).

The specific objectives of 1) addressed by DATLAS are:

Primary "Innovative development and manufacturing techniques": Laser welding as a high quality joining technique is often applied for complex products with high quality requirements. The

controllability but also the process knowledge of laser welding will be significantly improved, facilitating additional and advanced applications and in turn speeding up the development of complex products (e.g. applying advanced materials difficult to weld). Laser welding is an “enabler technology”, enabling to apply materials, design and functions (strength, quality) that are not possible with the traditional joining methods.

Secondary “Product data handling of complex products or systems”: DATLAS aims at widely replacing (usually manual) post-inspection of welds by highly automated on-line process monitoring, which inherently delivers electronic data. An application specific support software will be developed, to (beside other functions) collect, analyse and record data for tracing the welding process quality. Even a generic data self-learning function will be studied.

2) The attractiveness of research in lasers, laser processing and process monitoring will be stimulated through the DATLAS-project as it will (i) demonstrate the strong direct impact of high level experimental and theoretical science to industrial applications, (ii) deliver exciting videos and images from the welding process difficult to observe (as being little, hot, dynamic)

DATLAS addresses the research-oriented objectives of VINNOVAs KSP programme through establishing a complementary partnership expertise at a level of excellence, in particular by combining the modelling and experimental process expertise of the “manufacturing” division with the measurement expertise of the “experimental mechanics” division at Luleå TU, as well as the competence of seven companies of different kind.

2. Quality

2.1 Scientific State-of-the-Art

In the area of laser materials processing optical methods are most common for on-line quality monitoring. Optical sensors like photodiodes (often with spectral filters), pyrometers and recently cameras (particularly IR-thermocameras) are employed above (or below) the workpiece in order to collect thermal radiation originating from each surface element of the hot processing zone. The radiation of each surface element (or plasma volume) is based on the spectral emissivity, temperature (e.g. Stefan-Boltzmann law), surface condition and geometry (the sensor collects rays irradiating into half-space). Temporal variations of the process change its geometry and radiation appearance and therefore (often) the sensor signal.

Fig. 3 shows empirical correlations obtained by the applicant for (a) laser welding (welding through or not) and (b) laser cutting (burning damage or not)

However, due to the inductive information flow of optical sensors (collecting = integral over geometry and spectrum) information gets lost. The sensor collects radiation of various type and origin to a single abstract signal vs. time. The context to the original process is not obvious, although for some simpler cases a context could be found. Cameras provide a 2D-picture as additional information, but automatic image processing induces additional complexity.

Already applying the same sensors also for post-diagnostics (as is sometimes done) becomes much easier, as avoiding high temperatures and fast processes (although the low scale remains). Same for seam tracking systems, the method is easier: A line laser beam is projected onto a non-smooth joint geometry (e.g. fillet- or T-joint or with gap), the disturbed line being camera-detected and image processed. Such method is controllable and easy to understand.

Research on on-line sensors has been almost purely experimentally, mainly empirically. The only theoretical study performed was by W. Schultz (ILT Aachen) on radiation originating from a laser welding keyhole, with the important conclusion that a strong photodiode signal can originate from a collection of radiation from an almost vertical geometry (keyhole; although its projected surface is a tiny ring), enabling correlations to the depth of welding. Otherwise developed contexts reduce to very obvious correlations kind of: “Plasma generation (like shielding) in a certain spectral range/filter increases the signal” or “Laser line filters enable pure laser reflection detection (telling whether a keyhole has started or not)”.

The approach is based on eliminating a large part of the complexity of the process (the whole keyhole, absorption, heat conduction, fluid flow and plasma physics of laser welding), while calculating forwards from experimental evidence (measured surface geometry and motion), thus reducing the complexity of the problem to a certain physical mechanism (irradiation of the surface towards a photodiode sensor). The power of such approach was successfully demonstrated for drop detachment during MIG-welding (by MIT: from high speed imaging of the drop detachment the acting forces could be computed) and for pore formation during laser spot welding (by the applicant, at Osaka Univ¹: from X-ray high speed imaging the shape of the keyhole when collapsing led to calculation of the gasdynamic and surface tension mechanism responsible for a stable pore).

2.2 Advancement and added value through the present project

Figure 2 illustrates the cooperation of different methods to be applied as a highly innovative but challenging approach to understand the context between the defect mechanisms and signals. When a transient mechanism (e.g. keyhole collapse, Fig. 3(a)-(d)) causes a defect (e.g. pore), the monitoring system records a signal, Fig. 3(b), through thermal surface emissions. The surface will be qualitatively observed through high speed imaging, Fig. 3(c) and quantitatively by a series of triangulation sensors, Fig. 3(d). From the measured dynamic relief simulation (ray tracing) of the emissions, Fig. 3(b), shall predict the photodiode signal, to explain the context.

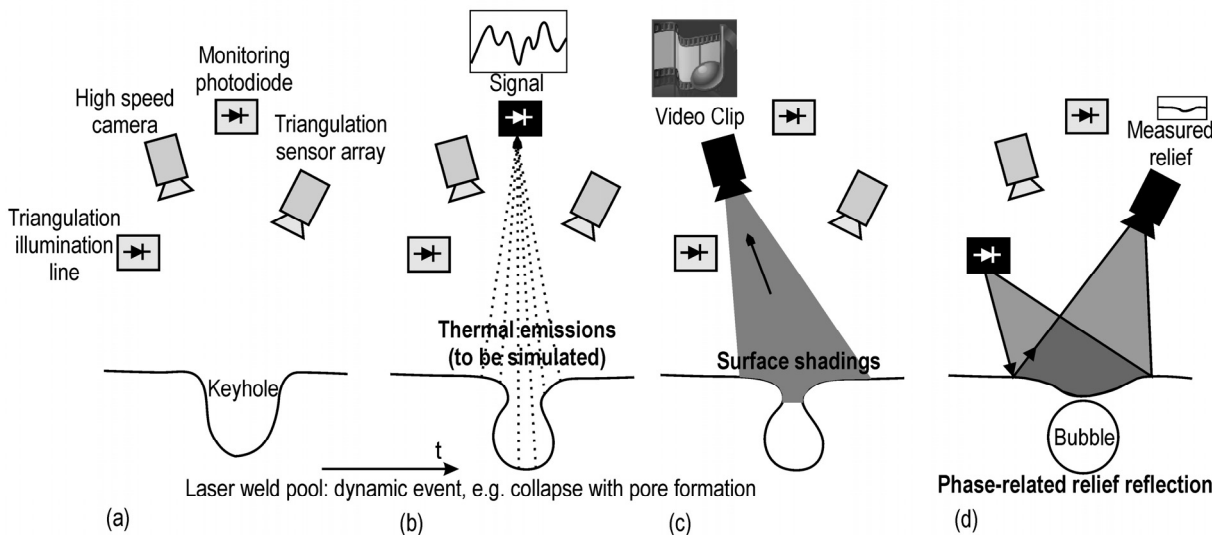


Fig. 3: Proposed method for identifying the surface geometry and motion (defect cause) as origin of resulting irradiation signal changes and in turn derivation of a theoretical context: (a) 3 observation instruments, (b) monitoring photodiode (emissions to be simulated by ray tracing), (c) high speed imaging (qualitative), (d) triangulation profile (quantitative)

In contrast to the experiment-based, empiric state-of-the-art of process monitoring, DATLAS aims at theory-supported and systematically generic research. Instead of developing one more case study, knowledge shall clearly converge to fundamental, generally applicable understanding of the context between signal and defect. In case of success the findings of the project will not only be highly valuable for improved, controlled application of process monitoring in industry, but from a scientific point of view will also lead to strongly improved process knowledge (particularly the physical mechanisms causing defects), which is still very unsatisfactory today. (also improved basic understanding will improve industrial applications) The understanding of discrepancies between defects and the sensor signal can also lead to advanced sensor development matched to the process in a better way (e.g. arrangement, type).

¹ Kaplan, A.F.H., M. Mizutani, S. Katayama, A. Matsunawa: Unbounded keyhole collapse and bubble formation during pulsed laser interaction with liquid zinc, *J Phys D: Applied Physics*, v 35, pp 1218-1228 (2002).

2.3 Verifiable indicators

- Number of additional entries (correlations, tracks) in the virtual support tool database
- Number of customers purchasing/receiving the tool from the Swedish SW-suppliers
- Number of companies applying the virtual support tool in production (in Sweden)
- Amount of cost reduction through reduction of post-inspection (per user)
- Increase in the percentage of reliability of process monitoring applications (per user)
- Number of new laser welding applications facilitated by addition of the support tool

3. Method and Workplan

3.1 Strategy and scientific method

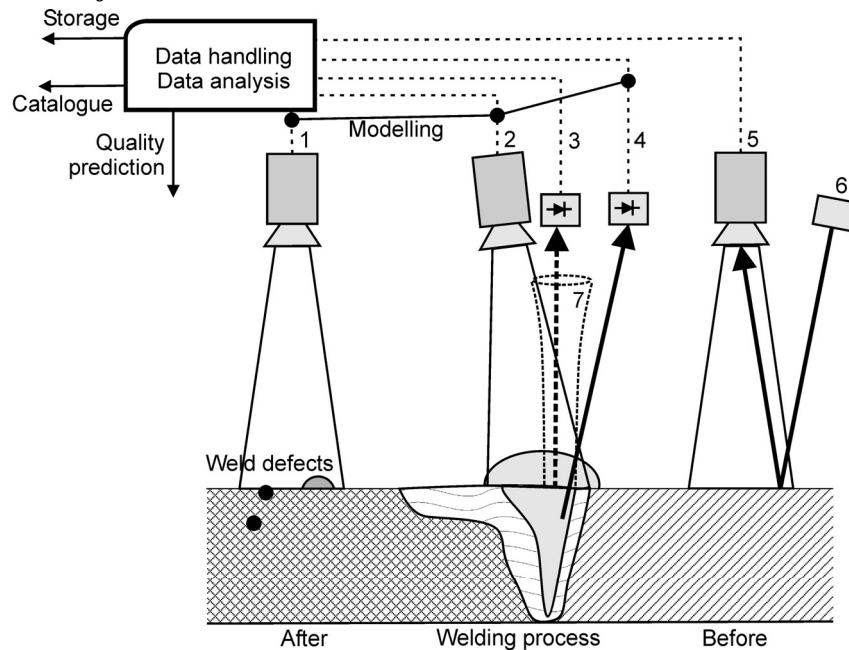


Fig. 4: Scientific approach: developing and modelling a correlation between conditions, surface motion, weld result and the sensor signal, and data handling

The overall strategy is as follows:

- Provocation of typical welding defects (for a number of selected demonstrator cases)
- High level observation, Fig. 3(c), and measurement, Fig. 3(d), of the transient surface motion (elevation) of the weld pool (defect event), accompanied by monitoring, Fig. 3(b)
- Catalogue collecting of a series of pairs of defect photos and signal change images
- Numerical simulation (spectral ray tracing, Fig. 3(b)) of the radiation from the measured surface motions (Fig. 3(d), weighted by emissivity and temperature dependence) to calculate the radiation impact (spectral weighted integration of incident rays) on a photodiode sensor
- Comparison between detected and calculated signal along with improvement iterations
- Derivation of an illustrative theory explaining the origin of different welding defects and the context between the signal and the physical defect mechanism
- Modelling of additional correlation to seam tracking and camera post-inspection data, Fig. 4
- Developing a generic model that gradually learns (context rules) from data-recording
- Developing a professional user interface and software, resulting in a support tool
- Improvement of the partners' monitoring applications due to better understanding

The key task of the project is sufficiently good measurement (in terms of spatial and temporal resolution, suppressing plasma radiation disturbances) of the melt surface motion when defects occur along with accurate computation of the surface radiation (characteristics, emissivity, disturbances) towards the sensor. In case of success this powerful combination (never done before) will tell the whole story of defects, i.e. their origins and the capability of on-line monitoring.

3.2 Workplan

Table 1: Work plan and time schedule, divided into subprojects and tasks

#	Task (leader)	Milestone	Year 1				Year 2				Year 3			
	Subtask	Deliverable	1	2	3	4	1	2	3	4	1	2	3	4
I	Set-up	Menu												α
A	Equipment choice	Equipment												
B	Demonstrator choice	Case menu												
C	Correlation experiments	Menu images												
D	Virtual tool environment	SW-interface												
II	Observation of melt motion	Motion data												β
E	High speed imaging set-up	Method												
F	Triangulation set-up	Method												
G	Experiments	Videos, data												
H	Illustrative conclusions	Theory												
III	Simulation of radiation	Mechanism							γ					
I	Simulation model set-up	Method												
J	Calibration experiments	Material data												
K	Simulation	Movies, data												
L	Illustrative conclusions	Theory												
IV	Context motion-signal	Correlation								δ				
M	Data comparison	Differences												
N	Iterative method improvement	Maturity												
O	Illustrative overall conclusions	Theory												
V	Additional data functions	Cooperation											ε	
P	Seam tracking experiments	Data												
Q	Post-inspection experiments	Data												
R	Data cooperation model	Model												
S	Testing of cooperation model	Impact												
T	Generic data learning model	Model												
U	Testing of generic model	Impact												
VI	Implementation	Mature tool												φ
V	Software development	Virtual tool												
W	Adaption to equipment	Integration												
X	Reliability testing	Impact												

Task I: Set-up

The project starts with a selection (Subtask A) of a suitable process monitoring system to be purchased or hired, acting as the reference system to be improved. In addition, available monitoring systems by some partners will be studied for comparison suitability. A high speed camera and triangulation sensors will be selected for investment or hiring. Each end-user will specify (B) a few demonstrator cases (products,corresponding laser welding), including quality criteria to be detected. Based on this set-up systematic laser welding experiments (C) will be performed for the whole selected menu, both at Luleå TU and at the industrial laser systems. The parameters will be chosen such that process defects will be generated and then documented (fotos). The accompanying process monitoring system will deliver corresponding signal images. The basic layout and functions of the virtual support tool will be decided. By programming a user interface (Subtask D), a database can be fed by the whole menu of process defect fotos and corresponding signal images (plus the processing data) as reference documentation (open for extension). (catalogue as a useful result!)

Task II: Observation of melt motion

High speed imaging of laser welding (the qualitative method) is a very challenging method to be optimised (Subtask E) in terms of optics, arrangement, filters, illumination, etc. Triangulation measurement of the laser weld pool elevation is a new (challenging) application, requiring exploration (F) and optimisation (arrangement, filtering, combined data handling...). Difficulties are the high temperatures (melt 3000 K, plasma 20 000 K) along with radiation, the small dimensions (sub-mm-scale) and the high speed (ms-scale), moreover limited access (e.g. keyhole interior).

The experiments of Task I will be repeated, now for observation and measurement (G) of surface motion and elevation, as origin of most quality defects (pores, undercuts, holes, spatter...). Highly illustrative video images and surface elevation data as a function of time (never measured before) will result. In case of success, from these scientifically and technically highly valuable results new theories (H) on the mechanism of laser welding and its defects can be derived and illustrated.

Task III: Simulation of radiation

The transient surface elevation data will serve as the geometrical boundary for simulation of the radiation. A simulation model (Subtask I) will be developed that calculates forward the radiation from these hot moving surfaces by ray tracing. Beside the radiation characteristics into space, the thermal radiation law, the emissivity (to be identified experimentally, Subtask J), the plasma interference, and the sensor location and its spectral behaviour will be considered. Simple calibration experiments with well defined hot moving samples will be carried out for optimising the model.

Based on the measured surface geometry motions the simulations will be performed (K). Again highly valuable results will be obtained, enabling manifold analysis (scientific novelty). Essential conclusions are expected, to be illustrated in form of a theory (L). The evaluation will focus on the radiation impact on the photodiode sensor, reducing all information to a time dependent signal.

Task IV: Context motion-signal

The most critical part of the project is the comparison (Subtask M) between the theoretical signal obtained through the surface measurement along with simulation and the signal obtained from the process monitoring system. Only the transient characteristics is of importance and will be compared. Discrepancies will lead to discussions for possible errors and improvements (N) of the methods in an iterative manner until satisfactory coincidence is achieved. Eventually from the successful prediction of the signal behaviour by the measurement and simulation method theoretical descriptions (O) of the context between surface events (i.e. defect creation) and signal changes will be achieved. In particular this understanding of the context will explain the limited reliability of today's monitoring systems and will enable system improvements (e.g. signal analysis or sensor arrangement) and in turn reliability enhancement (guided by the theoretical explanations).

V: Additional data functions

As several instruments could be applied for the same application, cooperation between their data would be appreciated. A model shall be developed to find correlations between the seam tracking profile (pre-process), the monitoring photodiode (on-line) and the inspection images (post-process). This additional information context will facilitate a correct interpretation.

The current data recording inherently provides highly valuable data on the process and product, beyond the direct quality-monitoring. A function for suitable data storage and handling will be provided, combined with a generic model to be developed (different approaches to be proven) that enables to converge towards a correct context interpretation in a self-learning manner.

VI: Implementation

The virtual support tool will be disseminated and taught at the companies, as a base for learning, discussion and signal analysis. The improved signal analysis strategies will be tested in production. The extra function of recording and analysing the sensor data will be applied. The 3 system suppliers will adapt the software, hardware, methods and results to their product range, then offering it at the market. The end-users will carry out long term reliability of the system developed.

3.3 Partners, competence and role

A) Luleå TU, Division of Manufacturing Systems Engineering: worldwide recognized experts in laser materials processing (particularly laser welding) for 26 years; laserlab (value 25 mkr) equipped with 7 high power lasers; experience in seam tracking, process monitoring, simulation

B) Luleå TU, Division of Experimental Mechanics: leading science in optical measurement methods (lab for interferometry, holography, LDV, etc.); will perform imaging, measurement

C) Alfa Laval Lund AB: product: heat exchangers (made of titanium or stainless steel); 3 laser welding stations operate in production; process monitoring system available - not satisfactory!

D) ESAB: inaugurated a hybrid (laser+MAG) welding laboratory in 2005 for customer support and process knowledge; interest in process monitoring tool for customer support

E) Ferruform AB/Scania: one of the most exciting laser applications in Sweden: laser welding of truck rear axes with a 12 kW laser through a patented system (fixturing/handling/process monitoring; together with LTU); still the monitoring does not detect some welding holes.

F) Lasertech LSH AB: Laser welding job shop (a challenge, as highly customer oriented) with 9 (!) high power lasers; high quality applications (military, micro) asking for monitoring

G) Laser Nova AB: Well equipped, partially scientific laser microwelding job shop; challenging precision and quality; own research in monitoring (phase transitions via thermal colours)

H) Optronic: Leading Swedish manufacturer of optical measurement and observation systems; contributes with its excellent combined triangulation system measuring surface elevation

I) Permanova Lasersystem AB: Manufacturer of laser processing heads, including seam tracking systems, interested in integrating process monitoring and supporting software

Table 2: Work contribution per partner per task

	A)LTU PU	B)LTU XM	C) Alfa Laval	D) ESAB	E)Ferru form	F) LSH	G)Laser Nova	H) Optronic	I)Perma- nova
I setup	10%	10%	10%	10%	10%	10%	10%	20%	10%
II observ	10%	50%	40%	60%	40%	40%	50%	50%	30%
III simu	30%	5%	10%	10%			10%	5%	
IV contxt	20%	20%	20%	10%	30%	40%	20%	10%	30%
V data	20%	10%	10%		10%			10%	10%
VI impl.	10%	5%	10%	10%	10%	10%	10%	5%	20%

3.4 Budget

Table 3: Overall budget per partner and co-financing (confirmed by Letters of Intent, enclosed)

Budget (tkr)		TOTAL	2006	2007	2008	2009
Industry (co-financing)	Alfa Laval Lund AB	700	200	200	200	100
	Lasertech LSH AB	600	100	200	200	100
	Ferruform AB/Scania	900	200	300	300	100
	Laser Nova AB	900	200	300	300	100
	Optronic	500	100	200	150	50
	ESAB	600	150	200	200	50
	Permanova AB	300	50	100	100	50
VINNOVA (funds)	Luleå TU PU	3 500	400	1 300	1 400	200
	Luleå TU XM	1 000	300	400	200	100
Sum	TOTAL industry	4 500	1 000	1 500	1 450	550
	TOTAL VINNOVA	4 500	700	1 900	1 600	300
TOTAL	TOTAL	2 600	1700	3 400	3 050	850

4. Exploitation and Implementation

4.1 Exploitation, dissemination, transfer

For exploitation the limits of DATLAS need to be explored and stated with respect to the scope of the catalogue, the reliability of the method, the potential of generic self-developing. Exploring the potential for transfer to other (laser or welding) techniques and disciplines will enter an interdisciplinary dimension. Moreover, the potential for applications in Sweden as well as worldwide needs to be identified. A suitable dissemination strategy will be developed and initiated.

Dissemination will be carried out at different levels, namely through publications of the scientific findings and through the established dissemination channels at the university and at those industrial partners interested in dissemination, e.g. home-pages (e.g. www.svelas.se), folders, seminars, etc. Important for dissemination will be the development of a convincing demonstrator, both, virtually and physically. For the end-users, particularly the larger companies, internal dissemination shall develop awareness and a positive attitude to DATLAS.

4.2 Implementation plan at the partners

The four end-users of process monitoring will act as demonstrator cases already throughout the project, leading to testing, planning and eventually implementing DATLAS in production. Internal dissemination (causing a positive attitude in case of success) and training will be required.

The three systems manufacturers will explore the possibilities and needs for adding the virtual tool as an extra (supporting tool) in their hardware product catalogue. A corresponding strategy for maintenance, updating (software, data) and customer support needs to be developed.

4.3 Risk factors

(i) High speed/high resolution imaging and measurement of the surface of the interaction zone (as boundary condition for the simulation) is challenging leading edge research due to the small interaction zone and time-scale resolution (10-100 μm , 0.1-1 ms). Moreover, the hot plasma plume (10-20 000 K) disturbs optical measurements, requiring appropriate spectral filtering/illumination. *Risk: 30%; Strategy: Putting efforts in leading edge research and best equipment (hiring ?)*

(ii) The successful simulation correlation depends on the spectral emissivity factor of the surface (as a function of temperature) and on scattering by the plasma, which both is difficult to identify. *Risk: 30%; Strategy: Efforts towards careful literature study, dialogue with leading scientists, calibration*

(iii) The correlation between welding defects and their fluidmechanic origin has been a big challenge. Such valuable fundamental aspect is a kind of high potential/high risk research. *Risk: 40%; Strategy: Critical dialogue with leading scientists; developing a theory; confirmation tests*

(iv) Even when discovering a context, it has to be proven whether this context can be generalized or whether it depends on the conditions. Discovery of a general context extremely facilitates monitoring while case-dependence strongly limits the performance and applicability. Therefore understanding of the very deep fundamental mechanisms would be powerful for the final system to be applied. *Risk: 20%; Strategy: Generalizing studies (checking far away process parameters)*

(v) The same is true for modelling the context between seam-tracking, in situ monitoring and post inspection, which fails if the context is not generally revealed. *Risk: 20%; Strategy: state a theory*

(vi) The approach of a self-learning algorithm gradually improving through growing company/application-specific input is again an innovative high potential/high risk approach. Success would lead to a very powerful, as self-learning tool diverging to new contexts by the user (even without deep research background) – but simply the method is new and unknown and therefore has no reliable strategy yet. *Risk: 70%; Strategy: just trying, exploring.*

(vii) DATLAS is based on improving commercial systems through additional IT-solutions rather than developing new (even if more promising) hardware solutions. This bears the risk of being dependent on perhaps rigid, inflexible software difficult to change. *Risk: 30%; Strategy: develop widely software-independent stand-alone solutions, even if less elegant/less integrated.*