Problem of quality assurance during metal constructions welding via robotic technological complexes

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Abstract. The problem of minimizing the probability for critical combinations of events that lead to a loss in welding quality via robotic process automation is examined. The problem is formulated, models and algorithms for its solution are developed. The problem is solved by minimizing the criterion characterizing the losses caused by defective products. Solving the problem may enhance the quality and accuracy of operations performed and reduce the losses caused by defective products.

1. Introduction

One of the most important problems that Russian machine-building enterprises currently face is that of reducing losses caused by defective products being made while performing welding operations. An effective way to solve this problem is the introduction of robotic technological complexes (RTC). At present, various systems for optimizing RTC functionality have been developed and practically tested. Analysis of their functional purpose shows that the attention is focused on the optimization of manipulators or auxiliary welding tools [1-3]. Besides, current systems commonly lack a solution to the problem of reducing losses caused by defective products.

Given considerations determine the relevance and practical importance of the article devoted to the development of tasks, models and algorithms for controlling the welding process in RTC by a criterion that allows one to minimize the losses caused by defective products.

2. Problem formulation

To develop the search algorithm allowing one to find a vector of control actions \( u^*(t) \in U \), which could for any admissible values of medium states vector \( x^*(t) \in X \) minimize in a given time period \([t_N; t_K]\) a criterion characterizing the losses caused by defective products:

\[
K = \int_{t_N}^{t_K} D(t, x, x', u, u')dt \to \min
\]

(1)
under limitations:

\[ F_k(t, x, x', u, u') \geq 0, k = 1, ..., n_1; \]
\[ F_k(t, x, x', u, u') < 0, k = n_1 + 1, ..., n_2, \]

where \( K \) is the goal function characterizing the losses caused by defective products manufacturing in a time period \([t_N; t_K]\); \( D \) – integrand damage function; \( X, U \) – sets of admissible values for matching vectors \( x(t) \) and \( u(t) \); \( t \) – current time; \( n_1, n_2 \) – known constants.

3. Problem solving approach

Solving the problem (1) using the calculus of the variation method is challenging due to a need to develop a complicated dynamic model that would take into account the numerous quantitative and qualitative characteristics of the technological process, and also because of the uncertainty of the model parameters over a time interval. That is why a heuristic solution method has been developed, which is presented below. The algorithm for optimization of the \( K \) criterion is based on a practically proven statement, according to which the problem of minimizing losses coming from defective products can be solved by developing and executing an action plan for control actions in the RTC welding process. Thus, the problem solution (1) can be reduced to minimizing the failure probability of the given plan on the time interval \([t_N; t_K]\):

\[ \int_{t_N}^{t_K} P(t, x, x', u, u') dt \rightarrow \min \]

An action plan for minimizing losses caused by defective products \( G \) has been developed, based on the events analysis and years of experience. This plan is presented in the form of a tree in which the vertices are actions of the plan, and the arcs determine the sequence of their implementation and their interrelation (Figure 1).

**Figure 1.** An action plan for minimizing the losses caused by defective products manufacturing while performing welding operations in RTC: \( Q_0 \) – to reduce the losses caused by defective products manufacturing; \( Q_1 \) – quality control inspectors should check the welding products; \( Q_2 \) – welding operators should control the quality during welding; \( Q_3 \) – programmer should
periodically monitor the program during welding; $Q_4$ – to provide for the availability of relevant technological documentation at the workplace; $Q_5$ – to conduct a quality control of the welded product; $Q_6$ – an operator should carry out an intermediate quality control of the welded seam; $Q_7$ – to control the protective gas pressure at the input of the RTC; $Q_8$ – to monitor the operation of the tactile tracking system; $Q_9$ – to control the current stability on the motor of the supply unit; $Q_{10}$ – to monitor the cleaning program; $Q_{11}$ – to control welding parameters in real time; $Q_{12}$ – to control the quality of welding torch clean-up; $Q_{13}$ – to control the stability of the welding arc; $Q_{14}, Q_{16}$ – to perform a visual quality control of the welded seam; $Q_{15}$ – to control the deviation of the welding current from the nominal current; $Q_{17}$ – to control the values of current on the power supply indicators for the feeder motor; $Q_{18}$ – to check the condition of the torch nozzle after cleaning; $Q_{19}$ – to control the work of the BRS-LC station mill; $Q_{20}$ – to perform a visual control of the welding arc checking for sparks, splatter, etc.; $Q_{21}$ - the operator should monitor the stability of welding parameters on the power supply indicators; $Q_{22}$ – to clean the welding torch manually, if necessary; $Q_{23}$ – to call for the adjusters if the welding torch is not cleaned properly; $Q_{24}$ – to control the pressure of the compressed air at the cleaning station; $Q_{25}$ – to call for the adjusters if there is insufficient pressure of compressed air at the cleaning station; $Q_{26}$ – the workshop technologist should carry out a periodic examination of documentation; $Q_{27}$ – the workshop foremen should control the relevance of the documentation; $Q_{28}$ – to monitor welding current values using the RTMON function; $Q_{29}$ - to monitor the values of the welding current according to the power supply indicators; $Q_{30}$ - to monitor the threshold values of welding current deviations in the RTPM function; $Q_{31}$ – to select the feeder motor current indication in the power supply main menu; $Q_{32}$ – to stop the welding process in case of the motor current unbalance by more than 10%; $Q_{33}$ – to perform visual inspection of the torch nozzle after cleaning; $Q_{34}$ – control the level of anti-sputter liquid; $Q_{35}$ – to control the welding speed; $Q_{36}$ – to control the voltage of the welding arc; $Q_{37}$ – to control the horizontal and vertical movements of the welding torch; $Q_{38}$ – in case of a voltage fluctuation by more than 10% in pulsed welding mode, stop the welding process; $Q_{39}$ – in case of exceeding the voltage by more than 5% in the linear welding mode, stop the welding process; $\Lambda$ - the conjunction symbol; $V$ - the disjunction symbol.

4. Mathematical model of problem solution

Minimum sections of the events diagram are defined to evaluate the probability of non-fulfillment of plan $G$. Minimum sections are classified by the number of elements they are composed of: one-, two-, three-element, etc. Those sections correspond to the critical combinations of events that lead to the production of defective products.

Minimum sections for the actions plan diagram are presented in Table 1.

| Type of section | Sections |
|-----------------|----------|
| one-element     | $Q_1$; $Q_2$; $Q_3$; $Q_4$; $Q_5$; $Q_6$; $Q_7$; $Q_8$; $Q_9$; $Q_{10}$; $Q_{11}$; $Q_{14}$; $Q_{15}$; $Q_{20}$; $Q_{21}$; $Q_{24}$ |
| two-element     | $Q_{16}$ – $Q_{17}$; $Q_{18}$ – $Q_{19}$; $Q_{26}$ – $Q_{27}$; $Q_{28}$ – $Q_{29}$; $Q_{30}$; $Q_{31}$; $Q_{32}$ |
| three-element   | $Q_{18}$ – $Q_{24}$ – $Q_{25}$; $Q_{22}$ – $Q_{24}$ – $Q_{25}$; $Q_{23}$ – $Q_{24}$ – $Q_{25}$; $Q_{28}$ – $Q_{29}$ – $Q_{30}$; $Q_{35}$ – $Q_{36}$ – $Q_{37}$ |
| four-element    | $Q_{35}$ – $Q_{36}$ – $Q_{38}$ – $Q_{39}$ |

A state graph is created for each section, along with a system of Chapman – Kolmogorov differential equations. The probability of plan on-fulfillment (i.e. the probability of defective products being made during welding due to a critical combination of adverse events) is derived from the
solution of this system. Figure 2 illustrates an example of a state graph for three-element section $Q_{18} - Q_{24} - Q_{25}$.

![Figure 2](image)

**Figure 2.** State graph for three-element section $Q_{18} - Q_{24} - Q_{25}$: 0 – all activities are performed; 1 – activity $Q_{18}$ is not performed; 2 – activity $Q_{24}$ is not performed; 3 – activity $Q_{25}$ is not performed; 4 – activities $Q_{18}, Q_{24}$ are not performed; 5 – activities $Q_{18}, Q_{25}$ are not performed; 6 – activities $Q_{25}, Q_{24}$ are not performed; 7 - activities $Q_{18}, Q_{24}, Q_{25}$ are not performed

For a three-element section, the problem (1) is reduced to choosing the intensity of error recovery actions $\mu^*_i(t), i = 1, 2, 3$, at which in the given time interval $[t_n, t_k]$ is:

$$K = \int_{t_n}^{t_k} P_i \left( P_0, P_1, P_2, P_3, \lambda_1, \lambda_2, \lambda_3, \mu_1, \mu_2, \mu_3 \right) dt \to \min$$

The limitations are formed using the Chapman-Kolmogorov differential equations system and have the following form:

$$\begin{align*}
\frac{dP_0(t)}{dt} &= - (\lambda_1 + \lambda_2 + \lambda_3) P_0(t) + \mu_1 P_1(t) + \mu_2 P_2(t) + \mu_3 P_3(t) \\
\frac{dP_1(t)}{dt} &= \lambda_1 P_1(t) - (\mu_1 + \lambda_2 + \lambda_3) P_1(t) + \mu_2 P_2(t) + \mu_3 P_3(t) \\
\frac{dP_2(t)}{dt} &= \lambda_2 P_2(t) - (\mu_2 + \lambda_1 + \lambda_3) P_2(t) + \mu_1 P_1(t) + \mu_3 P_6(t) \\
\frac{dP_3(t)}{dt} &= \lambda_3 P_3(t) - (\mu_3 + \lambda_1 + \lambda_2) P_3(t) + \mu_1 P_1(t) + \mu_2 P_6(t) \\
\frac{dP_4(t)}{dt} &= \lambda_2 P_1(t) + \lambda_1 P_2(t) - (\mu_2 + \mu_1 + \lambda_3) P_4(t) + \mu_3 P_7(t) \\
\frac{dP_5(t)}{dt} &= \lambda_3 P_1(t) + \lambda_1 P_2(t) - (\mu_3 + \mu_1 + \lambda_2) P_5(t) + \mu_2 P_7(t) \\
\frac{dP_6(t)}{dt} &= \lambda_2 P_3(t) + \lambda_1 P_4(t) - (\mu_2 + \mu_1 + \lambda_3) P_6(t) + \mu_3 P_7(t) \\
\frac{dP_7(t)}{dt} &= \lambda_3 P_3(t) + \lambda_2 P_4(t) + \lambda_1 P_5(t) - (\mu_3 + \mu_2 + \mu_3) P_7(t)
\end{align*}$$

(2)

where $P_i, i = 0, 1, \ldots, 7$ – the probability of control object transition to the $i$-th state.

Initial conditions are:
\[ P_0(0) = 1; \quad P_i(0) = 0, \quad i = 1, 2, \ldots, 7. \]

Using the exact values of numerical coefficients and variables \( \lambda_j, \mu_j \), \( j = 1, 2, 3 \) at a given time interval will demonstrate the probability of a plan non-fulfillment due to the combination of events corresponding to section \( Q_{18} - Q_{24} - Q_{25} \). Thus, by solving the system of differential equations (2) for all minimum sections in different moments of time, it is possible to evaluate the probability of the critical events combination that will lead to the manufacturing of defective products in RTC welding.

5. Problem solving example
In order to solve the problem (1), it is necessary to determine the values of numerical coefficients \( \lambda_j, \mu_j \). The faults that lead to the inability of plan \( G \) execution were defined based on the experience of operating the Kawasaki RTC with C40 controllers and Fronius welding equipment. These faults are listed in Table 2.

| Faults | Faults quantity, hours | \( \lambda_j \) |
|--------|------------------------|----------------|
| “no|ign” error (exceeding ignition readiness time) | \( \lambda_1 = 0.017 \) |
| Fault in the wire feed system (too high current in the feed drive) | \( \lambda_2 = 0.008 \) |
| “no|Arc” error on a power supply display (arc break) | \( \lambda_3 = 0.114 \) |

Actions to address these faults and the corresponding intensity are represented in Table 3.

| Error recovery actions | Intensity of recovery, hours |
|------------------------|-----------------------------|
| Cut off the end of the wire, press the torch trigger and increase the wire feed limit without igniting the arc in the settings. | \( \mu_1 = 2.9 \) |
| Replace the feeder motor and the pinch rollers | \( \mu_2 = 0.86 \) |
| Cut the loose end of the wire, examine the tip, clean the surface of the product | \( \mu_3 = 1.5 \) |

By substituting the values of coefficients \( \lambda_j, \mu_j \) in the system of equations (2), it is possible to calculate the probability of non-fulfillment of plan \( G \) for minimum section \( Q_{18}-Q_{24}-Q_{25} \). Similarly, the probability of the plan non-fulfillment for all other sections is calculated.

The results of the calculations are shown on the radar chart in Figure 3.

As shown, the highest probability (0.63) is attributed to minimum section \( C_{17} \) (non-fulfillment of events \( Q_{18} \) “to check the condition of the torch nozzle after cleaning” and \( Q_{19} \) “to control the work of the BRS-LC station mill”).
6. Conclusion
The models and algorithms suggested allow one to significantly reduce the losses from the manufacturing of defective products, to improve welding quality and the technological stability of welding via RTC.

Implementation of the developed mathematical foundation is planned to be carried out on the basis of JSC “Transmash” (Engels city, Russia) structural divisions using the methods [4, 5].

References
[1] Bartenev V, Jakun S and Al’-Ezzi A 2011 News of the Samara Scientific Center of the Russian Academy of Sciences 13(4) 288-293
[2] Dille M, Grocholsky B and Singh S 2010 Field and Service Robotics: Springer Tracts in Advanced Robotics 62 183-193
[3] Filaretov V, Zuev A, Gubankov A, Procenko A and Yukhimets D 2016 Proceeding - 2016 International conference on computer, control, informatics and its applications: recent progress in computer, control, and informatics for data science (IC3INA) 158–162
[4] Rezhikov A F, Kushnikov V A, Ivashchenko V A, Fominykh D S, Bogomolov A S and Filimonyuk L Yu 2017 Journal of Machinery Manufacture and Reliability 46(4) 370–379
[5] Rezhikov A, Dolinina O, Kushnikov V, Ivashchenko V, Kachur K, Bogomolov A and Filimonyuk L 2016 Indian Journal of Science and Technology 9(46) 107351