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Using a wavelet medium for computer-aided controlling the movement of unmanned vehicles along quarry routes

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Abstract

Introduction. *It is established that the most effective tool for monitoring and controlling the dynamics of current trajectories (CT) of unmanned vehicles (UMV) when moving along opencast mine routes in open pit mining is the wavelet transforms technique.*

Methodology. *A detailed analysis of the procedures related to the technology of converting 1D-current trajectory signals (CT-signals) into a multidimensional medium of time-frequency distributions (TFD) is carried out. The Wigner distribution is selected as a working distribution for processing CT-signals. This distribution is considered from the point of view of its ability to represent one-dimensional CT-signals of UMV in an information-intensive and functionally transparent format of specific TFDs.*

Research results and analysis. *On the example of curved routes, the nature of the so-called forward and reverse transients of CT-signals of UMV, formed in the subsystems of external and autonomous control (ECSS and ACSS) of unmanned vehicles, is considered. Mathematical tools are described for wavelet transformations: Gabor wavelet functions, the wavelet matching pursuit algorithm (MP-algorithm), and Cohen's class time-frequency wavelet distributions.*

Conclusion. *The procedures of processing the trajectory signals with using the means mentioned above make it possible to implement effectively the functions of controlling the UMV movement along current trajectories formed by the system on opencast mine routes.*

Key words: *unmanned vehicles; current trajectories; Gabor wavelet functions; wavelet matching pursuit algorithm; time-frequency distributions; wavelet medium.*

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Introduction. Existing domestic and foreign quarrying equipment operating in an autonomous (unmanned) mode [1] requires diversification and wider opportunities to apply new state-of-the-art computer-aided control systems for dump trucks.

With regard to progressive, sustainable and prospective development of strategies and tools for computer-aided control of the unmanned dump trucks operating in open pit mining [1, 2] and involved in process work in off-road conditions [3], it is reasonable to develop well-known (already existing and applied in practice) directions and create new ones based on advanced [4, 5] alternative control strategies to meet the ever-increasing demands placed on the production cycle efficiency and quarrying safety.

It has been shown in previous researches [2] that the most optimal mathematical technique – in terms of efficiency in applying it to control the dynamics of unmanned vehicles (UMV) when carrying out opencast mining on technological routes of quarry machinery – is an *unconventional wavelet transforms technique* [5, 6], which makes it possible to represent 1D-scalar signals [7], corresponding to current trajectories (CT) dynamics on the route, in an information-intensive and semantically transparent form.

Research aim. The present work aims to study the mathematical technique of wavelet transforms for computer-aided control and monitoring of UMV dynamics when moving along opencast mine routes [1, 2].

Research methodology. Let us consider the issues connected with the characteristics of signals formed in a hardware-software complex (HSC) and reflecting UMV current trajectories dynamics on technological routes.

The HSC directories contain the conditions of CT dynamics accordance (its deviation to the left/right from the nominal axial trajectory – NAT) to information "trajectory" signals $x(t)$: to the left – a signal with a decreasing instantaneous frequency, and to the right – a signal with an increasing one.

While considering the UMV current route trajectories parameters formed within the so-called S-frames [2] and the conditions of setting the deviation shape for some trajectory at its initial (forward) and terminal (reverse) segments relative to NAT, it is required to characterize the procedures of the computer-aided control of UMV movement along certain trajectories.

The forward segment is created by means of *sporadic disturbances* formed because of UMV coming up against some obstacles that should be detoured along a particular trajectory, while the reverse one is created due to dynamic *modal control* procedure activation [7]. UMV CT moving away from the NAT line corresponds to the forward segment. In this case, the time-dependent frequency signal (chirp signal – [5]) either decreases its instantaneous frequency at CT leaving to the left of NAT, or increases it when the trajectory deviates to the right of NAT. In the language of wavelet transforms, in this way the downward forward transient process (DFTP), or the upward reverse transient process (URTP) is created, with relation to the non-stationary-in frequency signals registered in scalar or time-frequency wavelet form.

As to the reverse segment of a current trajectory, it is formed by means of *forced-modal control*. UMV CT returns to the NAT line, while the instantaneous frequency of the trajectory chirp that controls the left/right deviation trajectory, increases/decreases to the frequency that determines the nominal axial trajectory of UMV movement. Thus, the process of UMV CT formation is underlain by the effect of frequency variation *of the chirp signal* which is a key element in the *set* of UMV routing procedures *stored beforehand* in the hardware-software complex of the computer-aided system controlling UMV movement along opencast mine routes.

Fig. 1 shows the fragment of a curved S-frame (spline frame) [2] of some UMV route with two combined current trajectories localized to the left and right of the nominal axial trajectory (NAT, depicted with a solid thin line). A_l and B_l indicate inflection points on forward and reverse segments of the left trajectory correspondingly; C_l is the inflection point *on the forward segment of the right deviation trajectory* formed as a result of sporadic disturbance action. D_l and E_l here are the points of dynamic forced-modal control procedure activation [7] on the left and right trajectories. The signal that characterizes UMV *right reverse trajectory*, takes the form of the first order aperiodic system pulse response [7]:

$$x(t) = w(t) = (k / T)\exp(-t / T).$$

This waveform returns CT to NAT faster than the second order aperiodic system step response [7]:

$$x(t) = k_{\text{н}}[1 - \left(T_3 / \left(T_3 - T_4\right)\right)\left(\exp\left(-t / T_3\right) + \left(T_4 / \left(T_3 - T_4\right)\right)\left(\exp\left(-t / T_4\right)\right)\right],$$

where $k_{\text{н}}$, T_3 and T_4 are signal parameters (signal gain factor corresponding to the initial segment of CT, and time constants).

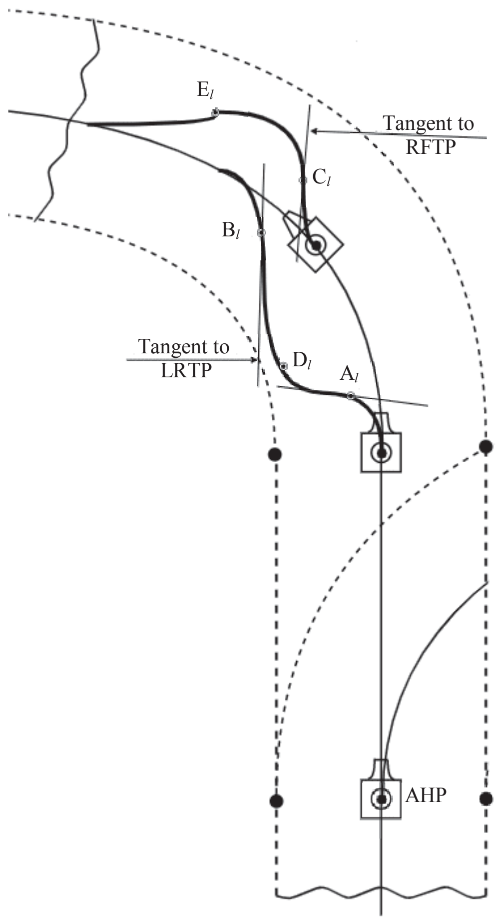

Fig. 1. Curved S-frame with an autonomous heavy platform available (AHP / UMV) and current trajectories leaving to the left/right of the nominal axial trajectory (NAT):
nominal axial trajectory (NAT) of UMV movement is depicted with a *solid thin line*; RFTP / LRTP (Right Forward Transient Process / Left Reverse Transient Process)

Рис. 1. Искривленный S-фрейм с автономной тяжелой платформой (АТП / БТС) и текущими траекториями, уходящими влево/вправо от номинальной осевой траектории (НОТ):
номинальная осевая траектория (НОТ) движения БТС изображена *сплошной тонкой линией*; RFTP / LRTP (Right Forward Transient Process / Left Reverse Transient Process) – правый прямой переходный процесс / левый обратный ПП

With the trajectory signal in the form of the first-order aperiodic curve, the possibility of UMV hitting against the bench face is prevented when moving along the *face-storage-bench face on the right* route and falling from the bench on *face-storage-bench* *face on the left* route. The opposite situation corresponds to UMV reverse movement along the storage-face route.

Under CT deviating to the left in S-frame concave section also leaving to the left, CT return to NAT under the action of the forced-modal control is smoother – in order to avoid overshoot (crossing NAT in the opposite direction) – according to the second-order aperiodic system. Herewith, the on-board lidar-radar-sonar unit [2] permanently scans the environment, particularly to detect an oncoming UMV.

First (right forward) transient process (TP) corresponds to the chirp signal with an increasing frequency, forming the *initial section of the right deviating CT*; UMV movement computer-aided control system generates it under the action of the sporadic disturbance on the route. Second (left reverse) TP is also characterized by the chirp signal with an increasing frequency since this process compensates UMV CT initial deviation returning the latter to the NAT line.

From the point of view of the chirp signal's character in the format of the time-frequency wavelet distribution, we will refer to such a process as the "upward forward TP" (UFTP). The terminal segment of the right deviation CT created by the *forced-modal control procedure* is correspondingly referred to as the "downward reverse TP" (DRTP).

Forward scalar transient processes like DFTP and UFTP, which determine the initial segments of UMV CT deviation to the left and to the right of NAT correspondingly, in wavelet medium are represented by the time-frequency distributions with decreasing and increasing instantaneous frequencies.

Note that reverse TPs in modal control mode for the S-frame curved right possess the same character as for the S-frame curved left. The difference in UMV CTs control for left and right route curvature is that for NAT lines different stationary frequencies of trajectory signals are set.

In order to provide information-intensive and semantically transparent processing the autonomous and external control subsystems (ACSS and ECSS) signals, fragments have been introduced into the software of the latter, which ensure the formation of the so-called wavelet functions [5, 6] and Cohen's class quadratic time-frequency distributions [5, 6, 8, 9].

Wavelet transforms technology is underlain by the concept of using: wavelet functions, wavelet matching pursuit algorithm (WMP) [5] and the associated specific Cohen's class distributions. Such *wavelet technology fragments* make it possible to relatively easily transform technological 1D-signals formed in ACSS and ECSS, into functionally transparent and information-intensive representations of such signals in a multidimensional wavelet medium [5, 6].

Similar video graphic representations on the screens of the computer-aided dispatching system (CADS) included in the structure of the global integrative system of "The Smart (intellectual) Quarry" [2], make it possible to continuously monitor UMV current trajectories and control their dynamics.

Furthermore, from the current wavelet representations [5, 6], the parameters of *upcoming* transient compensation processes of CT deviation from NAT are automatically calculated in the hardware-software complex. It opens up a possibility of creating certain necessary conditions for CT dynamic state control in order to return the CTs to NAT.

*The first fragmen*t put into the wavelet transforms technology represents a set (basis) of specific mathematical structures in the form of wavelet functions (wavelets). Such structures are of a two-axis localized form in a combined complex medium: they are time and frequency, as well as the *intensity, determined* by the instantaneous values of a wavelet function. They are needed for adaptive UMV CT 1D-signal waveforms approximation and as a result obtaining approximate signals in the form of a wavelet series [5].

Wavelets of Gabor basis have been chosen as wavelet functions that match approximated actual current signals of UMV CT dynamics [5] as closely as possible.

In order to analyze the trajectory (CT-) signals corresponding to UMV movement along open-pit mine routes, an array of Gabor wavelet functions (time-frequency dictionary) was used; it is invariant to time and frequency (t and ω) translation. Gabor dictionary is formed by scaling, translating and modulating a sine signal with a Gaussian window [5, 10, 11], which is relevant due to its ability to concentrate the signal energy on the t-ω-plane in the best way. The window is as follows:

$$\psi(t) = a \cdot \exp\left(j\xi(t-\tau) - (t-\tau)^2 \right),$$

where a, τ, and ξ are the Gaussian window parameters.

Wigner distributions [5, 9, 12] (our Cohen's class working distributions) obtained at Gaussian functions processing, always remain positive, which is imperative when interpreting the distribution as a joint distribution of signal energy density in time-frequency space. In the signal processing theory, such modulated Gaussian functions possessing least localization on the t-ω-plane, are called Gabor atoms.

For each scale 2^j, the discrete window of period N is created by quantization and periodization of a continuous Gaussian function:

$$\psi(t) = 2^{0,25}\exp(-\pi t^2); \qquad \psi_j[n] = K_j \sum_{l=-\infty}^{\infty} \psi\left(\frac{n-lN}{2^j}\right),$$

where K_j is determined by normalizing a wavelet function chosen from the dictionary, according to the quadratic norm [5, 8] $\left\| \psi_j \right\| = 1$.

Then, the window translates along t and ω. Let the index of parameters I of parameter field P of dictionary D for $(l, \xi) \in [0, N-1]^2$ and $j \in [0, \log_2 N]$ takes the form of $I = (l, \xi, 2^j) \in P$; here l, ξ, 2^j are discrete analogues for τ (translation), ω (modulated component frequency), s (scale parameter) for continuous wavelet functions. Then some Gabor discrete atom is as follows:

$$\psi_I[n] = \psi_j[n-l]\exp\left(\frac{j2\pi\xi n}{N}\right).$$

The resulting dictionary $D = \{\psi I\}_{I\in P}$ represents a set of atoms obtained by translation and is invariant modulo N. The wavelet matching pursuit algorithm (WMP), the kernel of *the second fragment*, carries out UMV current trajectory signal decomposition within the dictionary by grouping the atoms $\psi I+$ and $\psi I-$ with $I^{\pm} = (l, \pm\xi, 2^j)$.

At each iteration, instead of projecting the comb [5, 11] residual function $R_m(x[n])$ onto some atom ψ_I, the WMP procedure calculates its projection onto a plane made with the help of (ψ_{I+}, ψ_{I-}). As far as the function $R_m(x[n])$ is real, consequently, the approximation atom is a real vector as well:

$$\psi_I^{\varphi}[n] = K_{j,\varphi}\psi_j[n-l] \cdot \cos\left(\frac{2\pi\xi n}{N} + \varphi\right),$$

where $K_{j,\varphi}$ sets the unity norm of vector $\psi_I^{\varphi}[n]$, and the initial phase φ is optimized so as to maximize the scalar product [5, 10] of the atom and the residue $R_m(x[n])$; here $\varphi = [0, 2\pi]$.

The second fragment of wavelet transforms underlying the technology of 1D-signals representation characterizing UMV CT dynamics on a certain route, as mentioned earlier, is the wavelet matching pursuit algorithm. Its idea is to represent technological signals describing UMV CT dynamics, in the form of an approximation series consisting of wavelet functions with the corresponding coefficients that are determined as inner products of analyzed signal fragments about some current trajectory and Gabor wavelet functions extracted out of the dictionary.

By means of the WMP algorithm, adaptive local approximation of a signal is made. Decomposition of a CT analyzed signal is carried out as a total of time-frequency atoms extracted out of the wavelet dictionary [4], which efficiently correspond to signal residues at particular iterations:

$$x(t)=\sum_{n=0}^{m-1}\left\langle R_n x(t),\psi(t)_{\gamma n}\right\rangle \psi(t)_{\gamma n}+R_m x(t),$$

where $\left\langle R_n x(t),\psi(t)_{\gamma n}\right\rangle$ is the inner product (coefficient of a wavelet function within the wavelet series) of the residual polynomial $R_m\, x(t)$ of signal x at m-th iteration and wavelet function $\psi(t)_{\gamma n}$ selected from the thesaurus (dictionary), onto which the analyzed signal is "projected" in the course of its adaptive Gabor wavelets basis expansion.

This decomposition is described by the resulting time-frequency distribution of signal energy density, obtained by summing Wigner distributions $W\psi(t)_{\gamma n}\,(t,\omega)$ for all Gabor atoms $\psi(t)_{\gamma n}$:

$$Ex(x,\omega)=\sum_{n=0}^{\infty}\left|\left\langle R_n x(t),\psi(t)_{\gamma n}\right\rangle\right|^2 W\psi(t)_{\gamma n}(t,\omega).$$

Since the window is Gaussian, and the set of atomic parameters for an m-th iteration is $I_m = (l_m, \xi_m, 2^j{}_m)$, then the particular distribution $W\psi(t)_{\gamma n}$ represents a two-dimensional "ellipse" with the center in point (l_m, ξ_m) on the t-ω-plane, which is time/frequency-scaled with parameters 2^{jm} and $N \cdot 2^{-jm}$.

Thus, Wigner time-frequency distribution represents *the third fragment* of representation technology for the 1D-signals, which characterize UMV CT dynamics on an opencast mine route. It should be mentioned again that the given distribution refers to Cohen's class distributions [5, 6, 8, 9] that represent an extended set of similar multidimensional time-frequency distributions.

Research results, analysis. Wavelet matching pursuit algorithm makes it possible to assign particular modes in ACSS and ECSS hardware-software complexes for UMV nominal and current trajectories; the modes describe CT non-stationary fluctuations on the route and their time-frequency structures (ellipses, i. e. time-frequency atoms [2]) on the time-frequency plane. CT deviation to the left/right of the nominal axial trajectory of a route S-frame conforms to the corresponding atoms time-frequency localization change.

Wavelet matching pursuit algorithm adapting for processing the UMV CT signals, which, as a rule, are non-stationary in frequency, makes it possible to identify and monitor specific deviations of working trajectories conditioned by a current situation on the route. Time-frequency atoms (Gabor atoms) [4, 5] movement monitoring in time-frequency space, i. e. on a wavelet map [4, 9], makes it possible to control the dynamics of tracking CT and forced forming them, thus creating conditions for UMV rational behavior on technological opencast mine routes.

As a rule, well-known models are not able to take into account the combined effect that numerous significant factors have on UMV's required movement along a current route: UMV position relative to working bench faces, random autonomous-sporadic disturbances arising in the form of static or dynamic obstacles on a current route, dump truck speed varying, UMV movement along direct or curved NATs, the need for CT forced change relative to NAT within the limits of a particular S-frame, and etc.

Thus, in order to study the dynamics of CT formation processes, it is advisable to combine the cybernetic approach resting on the *input-output* models, the state-space method [7] based on the internal *input-state-output* models, and the time-frequency analysis based on wavelet transforms. Together they make it possible to adequately describe the over-all structure of UMV dynamics monitoring and control when moving along opencast mine routes.

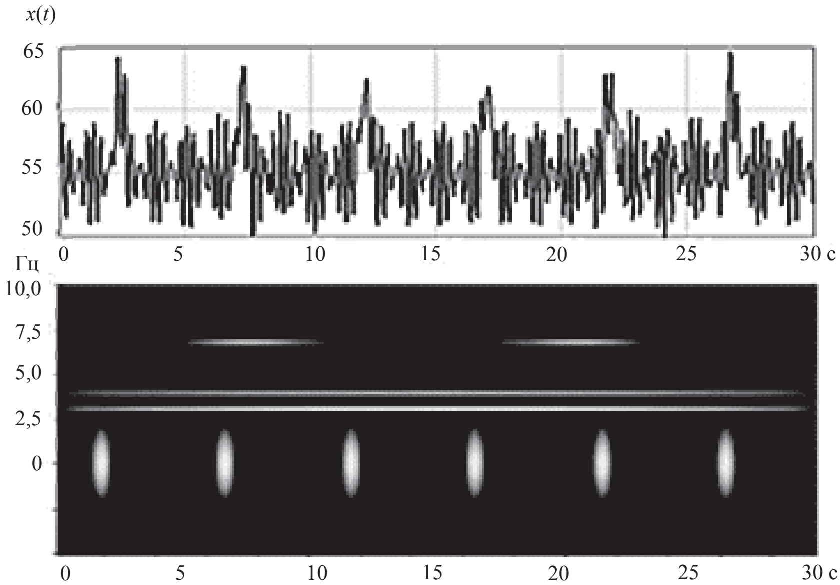

Fig. 2. One-dimensional current trajectory (CT) signal waveform $x(t)$ and the combined view as a time-frequency Wigner map representing the signals of AHP / UMV moving along direct trajectories for four various modes – *below*

Рис. 2. 1D-осциллограмма сигнала $x(t)$ о ТТ (вверху) и совмещенное отображение сигналов перемещения АТП / БТС по прямым траекториям в четырех различных режимах в формате двумерной время-частотной карты Вигнера (внизу)

On wavelet maps, as mentioned earlier, time-frequency atoms (Gabor atoms) movement monitoring in time-frequency space makes it possible to control tracking AHP/UMV current trajectories and forced forming of them. In particular, a wavelet map (fig. 2) shows the combined time-frequency distributions (TFD) for various current trajectories of UMVs moving along direct routes for four various modes.

The wavelet map shows the following modes of UMV movement:

– at a signal frequency of 4.02 Hz this TFD corresponds to the UMV current trajectory along the nominal axial trajectory with no deviation from NAT;

– the upper TFD describes the start-stop mode of UMV movement along the CT situated to the right of NAT, as soon as the technological signal frequency is higher (6.89 Hz > 4.02 Hz): moving for 4.5 s with a further pause for 13 s, and then again, moving for 4.5 s with a further stop for 7.5 s. Therefore, this TFD corresponds to AHP/UMV movement in the start-stop mode along the CT with a period of 17.5 s;

– the lower TFD adjacent to NAT TFD describes UMV movement along the CT lying to the left of NAT, because the frequency of the CT is 3.23 Hz < 4.02 Hz, here the latter is of NAT frequency;

– the lowest pulse TFD describes the start-stop movement of UMV along the CT lying to the left of the adjacent stationary CT (at a frequency of 3.23 Hz). Here, the cycle of the unmanned platform movement is as follows: movement for 0.7 s with a further stop for 5 s, after that the cycles repeat. This TFD shows how quickly (within 0.7 s) UMV can react to an obstacle on the route. TFD contains five full cycles with a start-stop mode period equal to 5.7 s.

Conclusion. The work presented considers the procedures of converting *one-dimensional signals*, which characterize the dynamic state of UMV CTs on coal pit mine technological routes, into *their multidimensional* time-frequency representations. The necessity of this kind of one-dimensional space signal functions transformation into the multidimensional wavelet medium makes it possible to information-intensive and functionally transparent monitor the dynamic state of UMVs in this medium and control their current trajectories on opencast mine routes in a computer-aided mode.

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Использование вейвлет-среды для автоматизированного управления перемещением беспилотных транспортных средств по карьерным маршрутам

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Реферат

Введение. *В работе установлено, что наиболее эффективным средством для контроля и управления динамикой текущих траекторий беспилотных транспортных средств (БТС) при их перемещении по карьерным маршрутам в условиях открытых горных работ является аппарат вейвлет-преобразований.*

Методология. *Проведен подробный анализ процедур, связанных с технологией преобразования текущих траекторных 1D-сигналов (ТТ-сигналов) в многомерную среду время-частотных распределений (ВЧР). Рабочим распределением для обработки ТТ-сигналов выбрано распределение Вигнера. Данное распределение рассмотрено с точки зрения его возможности представлять одномерные ТТ-сигналы БТС в информационно емком и функционально прозрачном формате специфических ВЧР.*

Результаты исследований, анализ. *На примере искривленных маршрутов рассмотрен характер так называемых прямых и обратных переходных процессов ТТ-сигналов БТС, формируемых в подсистемах внешнего и автономного управления беспилотными транспортными средствами. Описаны средства, формирующие структуру аппарата вейвлет-преобразований: вейвлет-функции Габора, алгоритм вейвлет-поиска соответствия, время-частотные вейвлет-распределения класса Коэна.*

Заключение. *Процедуры обработки траекторных сигналов с использованием указанных средств дают возможность эффективно решать задачи управления перемещением БТС по формируемым системой текущим траекториям карьерных маршрутов.*

Ключевые слова: *беспилотные транспортные средства; текущие траектории; вейвлет-функции Габора; алгоритм вейвлет-поиска соответствия; время-частотные распределения; вейвлет-среда.*

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БИБЛИОГРАФИЧЕСКИЙ СПИСОК

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