Conceptual Design of Ukrainian Reusable Single-Stage Rocket with Vertical Takeoff & Landing Capability

Lukin K. A.1*, Prisiazhnyi V. I. 2, Mitikov Y. A.3, Levenko A. S.2, Lukin S. K1, Pauk O. L.4

1Laboratory for Nonlinear Dynamics of Electronic Systems, LNDES at O. Ya. Usykov Institute for Radiophysics and Electronics, National Academy of Sciences of Ukraine (IRE NASU), Kharkov, Ukraine
2National Space Facilities Control and Test Center, State Space Agency of Ukraine (NSFCTC, SSAU), Kyiv, Ukraine
3Oles Honchar Dnipro National University, Dnipro, Ukraine
4State Enterprise Production Association ‘Yuzhmash’ Building Plant’ named after A.M.Makarov’ (‘YUZHMASH’), Dnipro, Ukraine

E-mail: lukin.konstantin@gmail.com

Abstract. In the paper we briefly describe conceptual design of Ukrainian reusable single-stage rocket demonstrator. The main objective consists in design, development and trials of a series of ‘Grasshopper’ demonstrators equipped with both the jet propulsion engine set and microwave/optical vision and measurement systems for the performing and control of its soft landing at the starting point. The greatest advantages of our design consist in availability of the results of previous developments of rocket engines and guiding systems for ‘Yuzhmash’ space ships, as well as advanced technique for real-time microwave 3D imaging using random/noise signals and MIMO1 radar operation mode with FPGA2-based signal processing.

1. Introduction
Successful launches by the private company Space-X (USA) in 2020 of spacecrafts with the return of the reusable first stage of the Falcon-9 Launch Vehicle (LV) has confirmed the stable trend of private space companies to the reuse of the LV stages saved due to soft landing after its mission is completed. This topic has been studied for quite a long period of time aiming its practical implementation. For example: apart from SpaceX and other US space companies, two private Chinese companies are testing their rockets with a reusable first LV stage that returns to Earth by soft and vertically oriented landing: ‘Space Transportation’ (NKSPACE) and ‘LinkSpace’ (based on ‘NewLine-1’ LV).

In addition, the vertical landing method reduces the size of the exclusion ground areas, does not leave carrier rockets in outer space, and the spacecraft launched into orbit can be returned by the carrier after its mission is completed. This is especially important for providing cost-effective spacecraft launches accounting the following:
- reduction of the LV cost due to its reuse;

1 MIMO stands for Multiple Input Multiple Output
2 FPGA stands for Field Programmable Gates Array
- prevention of fines for non-working units left in their orbits (this tendency is currently being worked out with the aim of reducing the debris in outer space);

- abandoning of the old XXth century spaceports, since for the launch and landing of such a rocket vehicle only a small size concrete pad is needed, which makes the rocket launch possible even in a relatively populated country, such as Ukraine.

There are a lot of R&D projects of such systems: New Shepard (USA) - 12 launches, the start of the New Shepard 4 (NS4) model was planned for 2020; ‘Kankoh-maru’ (Japan) - project; ‘Mod’ (Armadillo Aerospace, USA). McDonnell Douglas DC-X (USA), for example, has made 12 flights since 1992. The Space-X company is also engaged in such developments: ‘Grasshopper’ for Falcon 9, ‘Starhopper’ for ‘Starship’, ‘Superheavy’.

In the paper we briefly describe conceptual design of Ukrainian reusable single-stage rocket demonstrator. The main objective consists in design, development and trials of a series of ‘Grasshopper’ demonstrators equipped with both the jet propulsion engine set and microwave/optical vision and measurement systems for the performing and control of its soft landing at the starting point. The greatest advantages of our design consist in availability of the results of previous developments of rocket engines [1], and guiding systems for space ships, as well as advanced technique for microwave real-time 3D imaging using random/noise signals and MIMO radar operation mode with FPGA-based signal processing. The maximal height of the flights/jumps will depend on the jet propulsion available and will growth with advancing of the demonstrator.

2. Description of the Reusable Rocket based on RD-8 Engine

It should be noted that current achievements including reusability and vertical take-off and landing of rocket vehicles, are based on the twentieth century worldwide experience. So, for example, the possibility of reuse of the Zenit-2 LV (Ukraine) was considered at the stage of its design (1K77 rocket, a Soviet two-stage medium-class launch vehicle, design started in 1977), the possibility of reuse use was considered by the international company S7 Space, etc. Just about that rocket Mr. Elon Musk, the Space-X owner, said in his interview to CNN in 2017: “Zenit, it is probably the best launcher after ours”.

Moreover, a long-standing Soviet-era partner of ‘Yuzhnoye Design Bureau’ the ‘Mechanical Engineering Design Bureau’ named after V. P. Makeev [2], in Miass city, Russia, has been working on this topic independently since 1992. Its reusable rocket ‘Crown’ has undergone many changes (shown in Fig.1) but has not yet been brought to its completion stage.

![Evolution of the ‘Corona’ Launch Vehicle design with vertical start and landing](image)

Figure. 1. Evolution of the ‘Corona’ Launch Vehicle design with vertical start and landing

Ukrainian experience in design and manufacturing of Launch Vehicles is illustrated in Fig.2.
Our primary task is to assess a possibility of creating a reusable rocket demonstrator in Ukraine. Therefore, not a full-fledged project, similar to the above ‘Corona’ LV, is to be considered first, but the suggested Demonstrators of reusable rocket, hereinafter named as D-X-UA and D-2X-UA. The latter one will have a much larger fuel tank to provide a higher flight altitude.

It is seen from Fig. 2 that the rocket engine RD-8 is the most suitable for design and manufacturing of Reusable Rocket Demonstrators D-X-UA and D-2X-UA. The rocket engine RD-8 is under serial production in Ukraine as the steering engine for the ‘Zenit’ launch vehicle [3], 11D513. Its main performances are presented in the Table 1 below:

| RD-8 Main Performance                  | Value                      |
|----------------------------------------|----------------------------|
| Fuel                                   | Liquid oxygen + kerosene   |
| Ignition of fuel in the engine chamber | Starting fuel              |
| Engine thrust in vacuum, t.f.          | 8.0                        |
| Nominal specific thrust impulse at sea level / in void, | 309.0 / 342.0 |
| Absolute gas pressure in the combustion chamber, kg/cm² | 78                    |
| Absolute gas pressure at the chamber nozzle exit, kg/cm² | 0.05                   |
| Mass ratio of fuel components          | 2.4                        |
| Thrust-to-weight ratio                 | 21.03                      |
| Number of ignitions                    | 1 and more                 |
| Swing angle of the engine chamber      | ± 33                       |
| Engine running time in flight, s       | до 1100                    |
| Diameter, m                           | 3.7                        |
| Height, m                             | 1.67                       |

The D-X-UA rocket should automatically take off vertically up to 300 m height and, with the running engines, land back at the launch point according to the calculations of flight ballistics and possible corrections of the trajectory on its terminal part.
The D-2X-UA with an increased fuel reserve should take off up to 62 km altitude and launch a micro-launch vehicle with a femto-satellite into an elliptical orbit (the Rockoon principle is to be implemented), and after that land back at the launch point using both a parachute system and a working rocket engine, provided corrections of the trajectory of its terminal part with the help of orientation and guidance system.

3. Orientation and guidance system for landing vehicles D-X-UA и D-2X-UA

The main function of the Orientation and guidance system (OGS) for D-X-UA и D-2X-UA landing vehicles are as follows:

- Measurement of the vehicle coordinates and velocity vector;
- Estimation and prediction of the vehicle terminal trajectory;
- Comparison of the predicted and theoretical trajectories and estimation of the corrections;
- Transfer of the correction values to the actuators;
- Real-time 3D imaging of the landing surface and space volume above it.

The OGS suggested is to be capable of all whether and day & night operation in harsh environment, such as dust, sand and snow storms, etc. That is why a microwave high resolution multifunction radar system should be put into the basis of that system and it is the most appropriate sensor for providing of the above performance (Fig.3 and Fig.4).

![Figure 3. Side-view (upper raw) and top view (lower raw) of the reusable single-stage rocket demonstrator D-X-UA](image-url)
Microwave sensors of orientation and guidance system are depicted as green and red arcs of different lengths: Tx and Rx are transmitter and receiver, respectively, of microwave visual system for the landing coordinates measurement and elaboration of the control information for guiding/landing system.

In addition, other standard and readily available sensors will be used as well. Actually, the OGS to be developed for the vertical soft landing of the D-X-UA and D-2X-UA rockets will include (along with the above multifunction radar) a standard GPS receiver, gyroscope based inertial system, optical imaging sensors and actuators.

The most challenging part of the OGS is design of the microwave multifunction radar system. It should provide realization of all above functions, an, at the same time, fit the available space and geometry. To meet the above requirements, we suggest a microwave collocated MIMO Noise Radar concept. Noise Radar uses random noise waveform to ensure its jamming/interference resistance and high range resolution. ‘MIMO’ is abbreviation for ‘Multiple Input Multiple Output’ radar system. MIMO concept will be applied for realization of the following multifunction operational mode, providing:

1. Real-time 3D imaging based on 2D aperture synthesis and wideband noise radar;
2. Monopulse radar mode for detection of a beacon signal placed at the landing area and its position measurement using digital beam forming (DBF) technique;
3. Altimeter mode for measurement of the landing Demonstrator altitude using wideband noise radar and DBF technique.

The concept of such a radar has been elaborated in LNDES IRE NASU for 2D and 3D imaging ground based Synthetic Aperture Radar [4,5]. It has been implemented and tested in Ka-band for L-shaped antenna array and time division of the Transmit (Tx) and Receive (Rx) channels [6]. However, to speed up the data acquisition and image formation process we are planning to use multichannel receivers [7], while topology of the L-shaped antenna array will be transformed to antenna arrays of...
circular geometry as it is shown in Fig.3 and Fig.4. Here a simplified option of MIMO system is shown which uses four MISO radars: Multiple Input and Single Output, i.e. a single transmitter (red) and arch-like antenna array (green). Performing joint signal processing for all four MISO radars one may implement one of available options for this geometry MIMO radar system aiming realization of 3D and 2D imaging and through DBF – Monopulse radar mode, while altimeter function comes out as a gratis from this design: with 1 GHz bandwidth of the noise signal Power Spectral Bandwidth (PSD) the accuracy of altitude estimate is about 15 cm. The second option may be compound of the Receive and Transmit arch-like antenna arrays. These arches should be of 1 fourth of the rocket circle and place in alternating fashion. The latter option requires more transmitters, but it may help in providing better performance of sensitivity and angular resolution of the imaging radar.

4. Conclusions
1. The results presented in the paper should be considered as the first stage of feasibility study focused on implementation in Ukraine of a ‘Zenit-2’ type launch vehicle with reusable first stage.
2. As the main sensor for the Orientation and Guidance System of the Demonstrator we suggested a microwave MIMO noise radar sensor capable of working in multifunction mode, providing: (1) Real-time 3D imaging based on 2D aperture synthesis and wideband noise radar; (2) Monopulse radar mode for detection beacon signal at the landing point and its position measurement using digital beamforming technique; (3) Altimeter mode for measurement of the landing Demonstrator altitude using wideband noise radar and DBF technique. With 1 GHz PSD bandwidth the accuracy of altitude estimate might be about 15 cm.
3. Future launch, flight and landing trials will confirm results of theoretical studies, and will help to find ways for design enhancement. The latter will enable more precise formulation of the Demonstrator specifications for the design of advanced Ukrainian launch vehicles with reusable stages.
4. The results obtained will help in the future implementation of the design of a full-scale super-heavy single-stage launch vehicle with soft vertical landing to be used for various space missions.

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