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Development of an autonomous system for assessment and prediction of structural integrity

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Research Paper

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Development of innovative solutions for the maintenance of transport infrastructure facilities is needed in order to ensure a more rational, planned and lower-cost maintenance of transport infrastructure, and to ultimately minimise the risk of catastrophic consequences. A system for an autonomous inspection of structures, based on advanced measuring methods integrated on a wall-climbing robot and an unmanned aerial vehicle, is currently developed in the scope of the ASAP project. The objective of this paper is to provide an overview and draw attention to disadvantages of conventional methods for testing materials and structures in order to assess their condition. This objective was the main motivation for forming a multidisciplinary team through the ASAP project. Possibilities and challenges in the development of an autonomous structural-assessment system are also presented in the paper, with the purpose of increasing the reliability and efficiency of systemic assessment of structures.

Key words:
condition assessment, corrosion, frequency, visual inspection, wall-climbing robot, unmanned aerial vehicle

Prethodno priopćenje

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Razvoj autonomnog sustava za pregled i predviđanje integriteta građevina

Kako bi se osiguralo racionalnije, plansko održavanje prometne infrastrukture uz smanjenje troškova te u konačnici minimalizirao rizik od katastrofalnih posljedica, nužan je razvoj inovativnih rješenja u području održavanja građevina prometne infrastrukture. Kroz projekt ASAP razvija se sustav za autonomni pregled građevina, koji se zasniva na naprednim mjernim metodama integriranim na robota penjača i bespilotnu letjelicu. Cilj ovog rada je dati osvrt i upozoriti na nedostatke konvencionalnog načina ispitivanja materijala i konstrukcija za potrebu ocjene stanja, koji su bili osnovna motivacija okupljanja multidisciplinarnog tima kroz projekt ASAP. U radu su također prikazane mogućnosti i izazovi razvoja autonomnog sustava za pregled građevina, a sve u svrhu povećanja pouzdanosti i efikasnosti sustavnog pregleda građevina.

Ključne riječi:
ocjena stanja, korozija, frekvencije, vizualni pregled, robot penjač, bespilotna letjelica

1. Introduction

Transport infrastructure is one of the key capital assets of the Republic of Croatia (HR), with more motorway kilometres per 100,000 inhabitants than the United Kingdom, Italy, or Greece. More than 3,180 structures in the road network, and 548 bridges in the rail infrastructure, are currently operated in the RC. A systemic increase of investment in maintenance activities can be observed in the European Union countries with similar motorway network. While investment in the maintenance of road infrastructure in Austria, Denmark or the Czech Republic amounted to € 800 – 1,200 million in 2020, only about € 200 million were invested in the same year for such maintenance in Croatia [1], Figure 1.

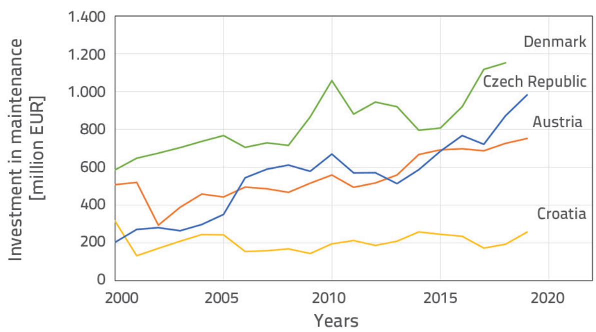

Figure 1. Comparison of total annual investment in the maintenance of transport infrastructure in the 2000-2020 period for Denmark, Czech Republic, Austria, and Croatia [1]

Insufficient systemic and proactive investments in the maintenance of the existing road infrastructure will lead to a reduced serviceability and bearing capacity of a great number of bridges, while also increasing safety risks to users of the Croatian transport infrastructure. It is expected that national investments in the maintenance of the existing transport infrastructure will have to increase significantly over the oncoming years considering the critical "age" of the existing structures, highly aggressive environment, and insufficient investment in maintenance over the past two decades. If appropriate measures are not taken at this moment, transport infrastructure of the RC will not only constitute a burden to national budget, but will also jeopardise the safety of its users, Figure 2.

Examples of bridge collapse, often followed by tragic consequences, are still quite frequent in all parts of the world. An example could be the bridge over the Mississippi River, Figure 3.a, which collapsed in 2007 causing 13 deaths and 56 injuries. A year before the sudden collapse it was concluded, after a regular inspection, that bridge repair would not be necessary prior to 2020 [2]. Another more recent example is the 2019 collapse of the Morandi Bridge in Genoa, Italy, resulting in 43 fatalities, Figure 3.b. Bridge inspections conducted in the period from 1990 and until a few years before the sudden collapse pointed to the poor condition and the high risk of sudden collapse of this bridge [3]. In addition, bridge collapse is often caused by extreme events such as earthquakes, as a considerable part of the existing infrastructure does not meet current seismic-design regulations.

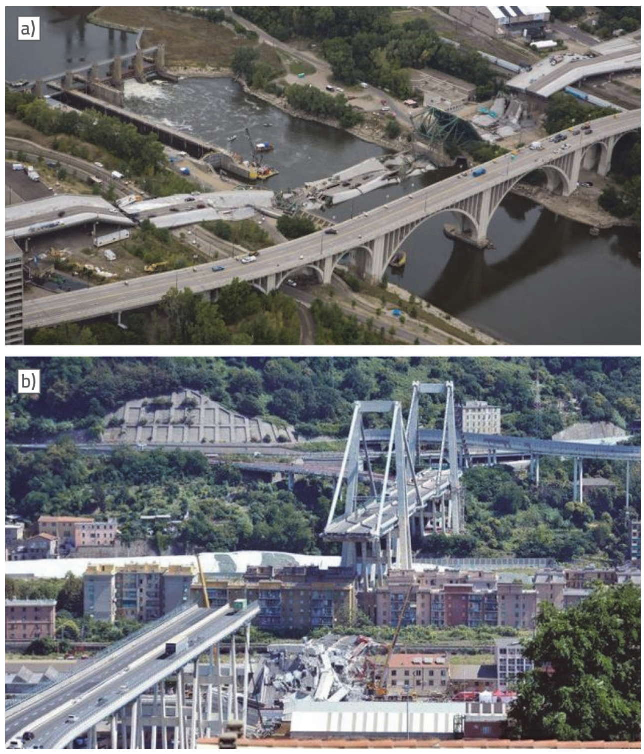

Figure 3. a) Collapse of the Mississippi River bridge in Minneapolis, USA, in 2007 [2]; b) Collapse of the Morandi Bridge in Genoa, Italy, in 2019 [3]

Figure 2. Damage to Bukovo Overpass on the Zagreb – Rijeka Motorway

A reliable assessment of the load bearing capacity and serviceability of structures can contribute to significant savings on the national level but, more significantly, to the safety of transport infrastructure users. In order to ensure a more rational and properly planned maintenance of transport infrastructure, and to minimise the risk of catastrophic consequences of an uncontrolled collapse of structures, it is indispensable to develop innovative solutions relating to the maintenance of

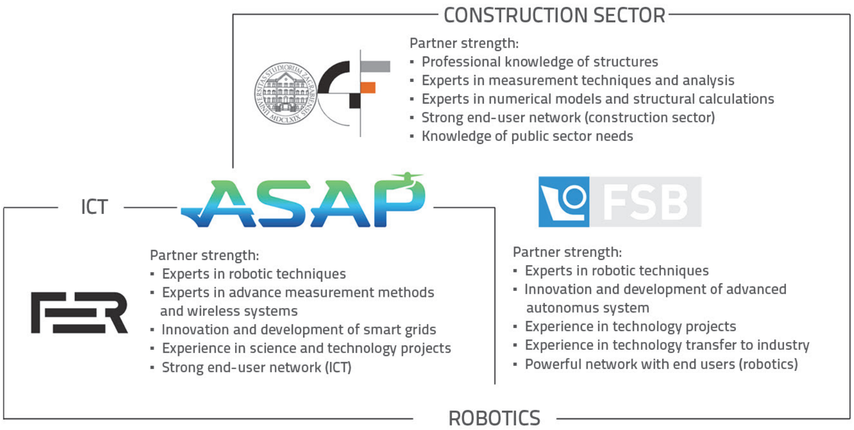

Figure 4. Complementarity of expertise of the project partners

transport infrastructure facilities. With this very objective in mind, the team of the project "Autonomous Systems for Assessment and Prediction of infrastructure integrity – ASAP" was assembled for the purpose of conceptualising a system for the autonomous assessment and prediction of the integrity of transport infrastructure, as a part of intelligent transport systems and logistics for the maintenance of the road and railway infrastructure, and for the monitoring and operation of such infrastructure. The system involves autonomous conduct of experimental testing of materials and structures assisted by a robot and an unmanned aerial vehicle, wireless data collection in real time that is followed by the post-process linking of the experimental testing and numerical modelling results for assessing the serviceability time and the remaining bearing capacity of structures, and establishment of a data storage concept in the form of a big data storage system, to be utilised by end users.

An innovative solution for the transport infrastructure maintenance logistics, as proposed in the scope of the ASAP project, is based on the unification of three areas into an interdisciplinary whole: a) measuring methods and numerical models for predicting integrity of transport infrastructure (Faculty of Civil Engineering, University of Zagreb, GF), b) autonomous robotic systems (Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, FSB) and unmanned aerial vehicles (Faculty of Electrical Engineering and Computing, University of Zagreb, FER LARICS), and c) advanced measuring units (Faculty of Electrical Engineering and Computing, University of Zagreb, FER ZOEEM), Figure 4.

The idea on the use of automated structural inspection systems, aimed at reducing building inspection costs and increasing reliability of post-inspection bearing capacity assessments, is currently being developed by several international teams. The simplest solutions that are developed involve only visual inspection [4, 5] or only one test method [6], or only movement along horizontal surfaces [7]. Compared to the developed solutions, the system that is currently under development in the scope of the ASAP project involves an integrated assessment and prediction of structural integrity, including:

- measuring system for locating reinforcement and mapping corrosion of reinforcement, integrated on a wall-climbing robot,
- measuring system for visual inspection, crack detection and monitoring, installing sensors, and collecting data relating to deformations and dynamic parameters of structures, integrated on an unmanned aerial vehicle,
- linking experimental parameters with numerical models for estimating serviceability and assessing bearing capacity of structures,
- automatic storage of measured data for a more efficient and safer operation of structures.

Each of these parts involves some specific challenges that are being solved by interdisciplinary teams in the scope of the ASAP project. Challenges relating to the first two steps in the development of the ASAP system will be presented in this paper:

- challenges of developing a wall-climbing robot with an integrated measuring system for locating and mapping corrosion of reinforcement
- challenges of developing an unmanned aerial vehicle that will be able to perform visual inspections and detect cracks, but also to install sensors for measuring relative deformations and vibrations.

2. Development of wall-climbing robot (RoKo) for determining condition of reinforcement

2.1. Traditional inspection procedure

According to the Building Act [8] and Technical Regulation for Engineering Structures [9], bridge operators are required to perform main inspections every five years, or every six years, as specified in the Roads Act [10] and the Byelaw on Road Maintenance [11]. In the current practice, traditional main inspections involve assessment of the condition of concrete, and assessment of the condition of reinforcement with regard to corrosion risk and, if practicable, determination of the chloride content [12] or carbonation depth. A whole array of electrochemical and non-electrochemical methods is available for determining condition of reinforcement as to corrosion levels [13]. Among them, the electrochemical methods based on potential measurements are nowadays most frequently used in the engineering practice. The method itself involves closing the electric circuit between the reinforcement within concrete (working electrode) and the counter electrode and the reference electrode that are located in the device itself. A disadvantage of measuring solely this reinforcement potential lies in the fact that test results can only be expressed qualitatively, by estimating probability of the occurrence of corrosion. The corrosion potential measurement result cannot be expressed in engineering units, such as through the loss of reinforcement diameter over time, which could then be used in the very calculation of the remaining bearing capacity and serviceability of the structure. Regardless of this deficiency, the measurement itself has been accepted by the profession, and is specified in an appropriate US standard [14]. Examples presented in Figure 5 show measurement of reinforcement potential in concrete. The example given in Figure 5.a shows the zones on the tested surface presenting a higher corrosion risk, as the measured potential is clearly negative. On the other hand, the entire measured surface presented in Figure 5.b consists of reinforcement presenting low corrosion risk, as greater potential values were determined.

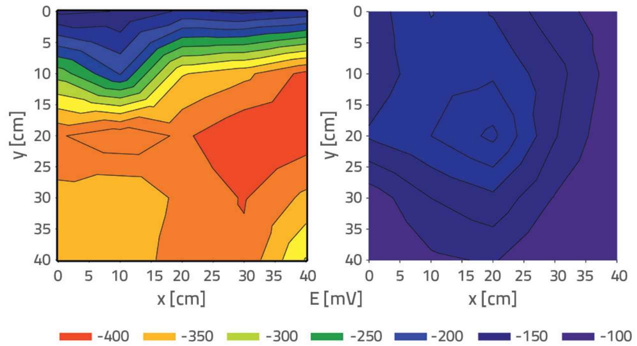

Figure 5. Reinforcement corrosion parameters in slabs in XS3 environment: half-cell potential [15]

On the other hand, corrosion current measurements enable measurement of the corrosion process kinetics while also providing information about the corrosion-process advancement rate in millimetres per year. When the age of the structure and the corrosion process advancement rate are known, it is possible to calculate the expected diameter loss of the rebar in concrete and, hence, to check the serviceability and bearing capacity of the structure. An example of the corrosion current measurement with calculation of the corrosion depth based on measured data is presented in Figure 6. The potentials measured over time (dotted line) reveal that a sudden drop in potential occurs after 210 days of exposure, which points to a higher probability that corrosion will actually occur. It can be seen that in all other days following 210 days the potential value is low, i.e., it amounts to approximately -400 mV which, even according to the American standard, points to the 90 percent probability of corrosion occurrence. On the other hand, calculated corrosion depths (solid line) based on corrosion current measurements enable accurate determination of the rebar loss due to corrosion. Once the rebar diameter loss is known, it is possible to calculate the remaining bearing capacity of structural elements.

The reinforcement condition determination is considered to be one of the key parameters as it can warn about the risks despite the absence of visible damage on the surface. On top of that, at the moment when the damage is already visible on the surface the corrosion process will have already greatly advanced and the repair needed will be broader in scope and more expensive. On the other hand, early detection and quantification of the corrosion process can greatly reduce the repair cost or avoid such cost altogether if adequate maintenance is provided. This is clearly visible on the example given in Figure 7 presenting corrosion potentials measured using the corrosion monitoring systems installed in big Croatian motorway bridges [18]. More negative potential values point to the corrosion risk, while the values that are more positive (or less negative) reveal a lower risk of corrosion. It is therefore possible to use the potential to determine the zones in concrete elements with a higher risk of the occurrence of corrosion. It can be seen in the figure that the potential values actually change during the service life of the structure, and that these values clearly point to critical parts of the structure, which can then be protected on time, or maintain in such a way to prevent uncontrolled deterioration and higher repair costs.

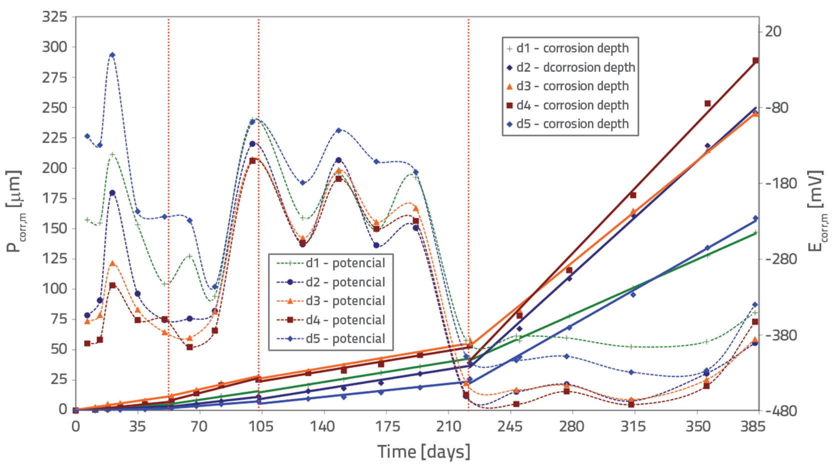

Figure 6. Potential and current measurements, and calculation of corrosion depth based on the current measured in RC beams exposed to simulated marine environment [16, 17]

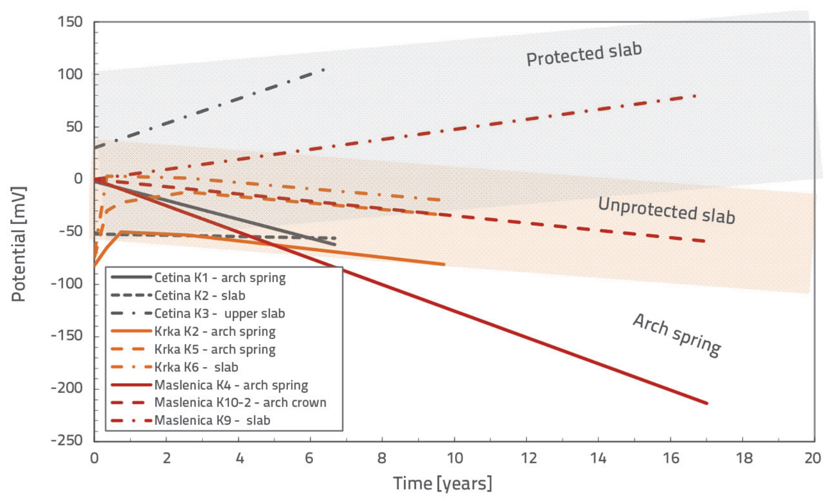

Figure 7. Corrosion potentials at various parts of the structure, measured with corrosion monitoring sensors installed in the Maslenica Bridge and in bridges over the Krka and Cetina rivers [18]

In any case, before the measurement of corrosion parameters, it is necessary to locate the reinforcement and to ensure connection with the reinforcement. Traditional reinforcement locating methods are based on eddy currents and, in such procedures, the instrument signalises when a metallic object is near it. If the only metallic object near the instrument is reinforcement, then it is possible to register the distance between the reinforcement and the instrument, i.e., the thickness of the concrete cover, Figure 8.

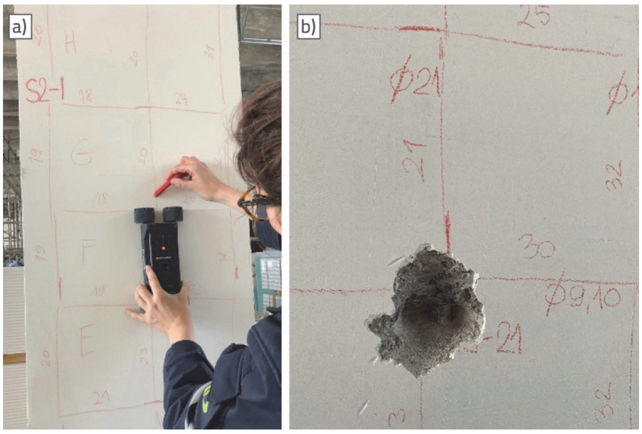

Figure 8. a) Locating reinforcement, determining concrete cover thickness and rebar diameter using instrument based on eddy currents; b) Confirming rebar position by opening the concrete cover [19]

Determining reinforcement location and its parameters is of highest significance during condition assessment and when assessing the remaining bearing capacity and serviceability of the structure. Usual methods involve manual measurements on selected locations. The measurement is performed by first locating the reinforcement and by making connection with the reinforcement making sure that safe connection is ensured in at least one point with other rebars in the element. After this step, the corrosion testing is conducted. The concrete must be conductive, i.e., it must be sufficiently moist in order to enable reliable corrosion measurements. This is especially significant in the case of corrosion current density measurements. If the concrete is completely dry, it will be impossible to measure corrosion parameters with sufficient accuracy. That is why the locations in which corrosion measurements are planned must be properly wetted prior to the measurements.

The described methods are time consuming, and their use is limited to measurements in smaller zones and at a smaller number of locations. The use of such methods is particularly challenging at inaccessible locations, where scaffolding or special vehicles must be used to ensure proper access to the zone in which the measurement will be made. In such cases, the testing is unsafe for inspectors, and involves a high safety risk for persons conducting the inspection, and also a considerable safety risk to transport infrastructure users. In addition, manual testing on smaller surfaces may result in the inconsistency of the results obtained by different inspectors. As no harmonised protocol is currently applied for the inspections and the use of experimental parameters, the assessment of serviceability and bearing capacity depends on the competence and expertise of the persons making the assessment. However, such persons are often changed because of public procurement rules. Finally, the testing itself can be economically inefficient as it involves: the use of expensive mechanical plant or the assembly of an auxiliary scaffold for inspection of hardly accessible zones, a considerable number of working hours, and closure of the affected traffic lanes or the entire road, resulting in considerable indirect costs.

2.2. Plan for development of the autonomous system RoKo

Because of all the above-mentioned deficiencies in the traditional testing of reinforcement condition within concrete structures, the ASAP project includes development of the measurement system for the simultaneous radar-assisted identification of reinforcement and the reinforcement corrosion mapping based on the potential-measuring electrodes, all integrated on a wall-climbing robot. The very development of such an automated measurement system includes, on the one hand, development activity in the use of the ground penetrating radar (GPR) for estimating condition of concrete structures and, on the other hand, the conceptualisation, development, design, and computer simulations of the wall-climbing robot.

In the segment involving condition assessment of concrete structures, the system development requires investigation of the current state-of-the-art in the GPR use for determining the position of reinforcement and the thickness of concrete cover, as well as the possibilities for using the same device for determining the condition of reinforcement as to corrosion threat [20, 21]. It is necessary to determine in laboratory conditions the level of applicability of the GPR during identification of reinforcement, as related to concrete condition and its electrical resistance (moist or dry condition, saturation with chlorides). Based on laboratory testing, it might be possible to determine calibration curves for linking the half-cell potential measured with electrodes and the corrosion current measured with field potentiostats, so as to derive from corrosion parameter measurements the information – as accurate as possible - relating to the thickness of the reinforcement layer that deteriorated due to corrosion. Furthermore, experimentally determined parameters can serve for developing initial numerical models aimed at predicting service life of structures.

In the segment involving the conceptualisation and development of the wall-climbing robot, the focus is on investigating the existing methods and developing new or improved methods for the start-up and adhesion of the robot structure to vertical surfaces of structural elements. The practical applicability of various operating concepts will also be checked in the scope of project activities:

- remote control of the robot's operation,
- development of control models for fully autonomous operation of the robot,
- hybrid control models based on the remote control and autonomous operation.

2.3. Challenges in the development of the autonomous system RoKo

Two principal challenges must be solved in the development of an autonomous robotic system: a) robust adhesion of robot to the surface, not greatly dependent on surface condition, and b) multidirectional and continuous robot movement along vertical surfaces. During a detailed inspection of measuring instruments (GPR device and corrosion potential measuring instrument), the decision was made to use the following measuring equipment because of compact dimensions (and upgrading possibilities): i) GPR type StructureScan Mini XT (f = 2.7 GHz), manufactured by GSSI (Figure 9 a), and ii) Profometer Corrosion with an electrode on the movable wheel, manufactured by Proceq (Figure 9 b). Considering the measuring equipment selected and the factor of safety, the carrying capacity of the robot should be at least 1.5 kg (GPR and HCP with appropriate electronics and power supply). Considering the scanning range (up to 10 square metres), the vertical range of up to approximately 30 metres, and the scanning rate (0.25 m/s), the operating time of the robotic system should be no less than 30 minutes.

Figure 9. a) Locating reinforcement and determining concrete cover thickness using GPR StructureScan Mini XT, b) Measuring half-cell potential with Profometer Corrosion

In order to determine condition of reinforcement with the GPR, it is necessary to conduct a grid scan, with vertical and horizontal scanning lines spaced at 10-30 cm intervals, depending on the scanning requirements. The grid scan must be conducted on a previously planned part of the load bearing structure and, therefore, the robotic system must be accurately and autonomously guided to the required location. To enable an accurate - both relative and absolute - movement of the robotic system, the system is equipped with sensors for measuring internal conditions (inertial measurement units, encoders) and also with sensors for measuring external conditions (optical flow sensors, vision systems).

Various robotic locomotion mechanisms, i.e., various ways of moving along a surface, have been described in the professional and scientific literature [22, 23]:
- bioinspired locomotion systems (arms and legs)
- locomotion by means of cables or guides
- locomotion by means of wheels or tracks

Bioinspired locomotion systems are of highest complexity considering the number of degrees of freedom of motion, and the need to apply advanced guiding algorithms. These systems are most often realised as four-legged or six-legged mechanical walkers. The basic problem with these walking robots lies in intermittent movements that cannot ensure continuity in the movement of measuring equipment, which is indispensable for assessing condition of reinforcement. Locomotion by means of cables and guides is a very robust system as it makes use of an auxiliary load carrying infrastructure. This principle cannot be applied on the ASAP project as load bearing columns and other infrastructure cannot be equipped with cables or guides. Locomotion by means of tracks does not enable multidirectional motion considering possible robot controlling configurations, and so the locomotion by means of wheels has finally been selected as a preliminary concept. The locomotion on wheels is the most flexible option when considering project requirements and, if combined with a specific type of suspension, it enables movement on even the most demanding surfaces.
To enable robot movement along vertical surfaces, it is also necessary to ensure a robust adhesion system, i.e., a system that will enable adhering onto a vertical surface. Five main adhesion types have been described in the literature [24-27]:
- magnetic adhesion
- electrostatic adhesion
- chemical adhesion
- mechanical adhesion
- adhesion by pressure and negative pressure.

As to the testing of reinforced-concrete (RC) structures in which reinforcement is situated at a certain depth, the adhesion with magnets (electromagnets or permanent magnets) is not suitable because of realisation of very low forces, and due to a great ratio of magnet mass to usable force. The electrostatic adhesion and chemical adhesion also offer very low carrying capacities that are insufficient for the parameters specified in the project, and are incapable of supporting the weight of measuring instruments to be carried by the robot. Mechanical adhesion makes use of the surface roughness, and the robot can adhere to the surface using various micro-needles, claws or other mechanical elements. Considering a wide range of possible surface roughness, this method would also be unable to ensure a robust adhesion. In addition, all of the above-mentioned adhesion systems require intermittent separation from the surface, which makes it difficult to ensure continuous motion. Therefore, the hybrid system of pressure and negative pressure emerges as the best solution because it enables generation of continuous and controlled vertical and horizontal forces, depending on the configuration of the device for generating pressure and

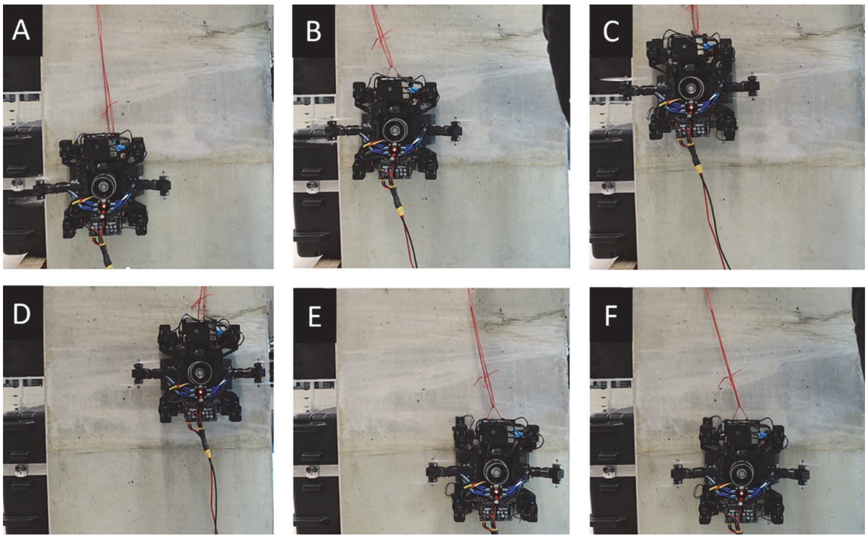

Figure 10. A to F movement test: RoKo robot is hand-operated to enable testing of its subsystems (mechanical subsystem, power subsystem, drive subsystem, adhesion subsystem, and operation/control subsystem); red rope is used as a safety measure, and it does not facilitate robot movement

negative pressure. Functionality of hybrid adhesion systems can be further studied in paper [27] where their experimental validation is presented. The combination of adhesion through pressure and negative pressure provides the adhesion force that is sufficient for enabling vertical and horizontal movement of the RoKo robot.

The current prototype of the RoKo robot (Figure 10), with a small propeller positioned near the robot's centre of gravity and one electric ducted fan (EDF), uses its compact structure to create negative pressure. The robot measures approximately 380 x 300 mm, and its total mass is 3.25 kg. The prototype has been additionally optimised with respect to the power to mass ratio, and it uses an all-directional movement system with four independently powered wheels capable of independently rotating about the axis perpendicular to the surface (swerve drive). In this way, the direction of travel can be changed in any point, enabling any direction of scanning once the RoKo is equipped with the GPR. The oncoming version of the robot will be improved so that it can carry the GPR on the rotating mechanism thus enabling vertical and horizontal scanning of reinforcement. The first successful tests of all-directional movements of the RoKo robotic system were carried out on an RC element measuring 80 x 120 cm, as shown in Figure 10.

Further investigations and improvements of the RoKo robot are continuously performed in the following areas: 1) optimisation of adhesion force, pressure, and power consumption of the hybrid adhesion system using an experimental laboratory setup, 2) development of a control algorithm for the new hybrid adhesion system, 3) development of a power system based on a high voltage source of direct current and 400-24V DC/DC converters, and 4) development of a communication system and communication protocol for communication between RoKo and the ground station.

3. Development of unmanned aerial vehicle for visual inspections, crack detection and installation of sensors (BePo)

3.1. Traditional bridge inspection and testing procedure

Main inspections of bridges include mandatory and highly detailed visual inspections of the structure, which often requires the use of cranes or installation of scaffolds so as to enable access to hardly accessible elements of the bridge substructure. At many bridges and viaducts, it is impossible to use traditional truck cranes or to install scaffolds because of poor accessibility of the terrain, or due to the height of piers. Special cranes with articulated telescopic buckets or platforms must be used in such cases, Figures 11 and 12. Although these operations are not particularly demanding, the use of such cranes on pavement structures implies either limited or full closure

Figure 11. Inspection of Franjo Tuđman Bridge in Dubrovnik, 2005 [28]

Figure 12. Examples of special bridge-inspection cranes [29]

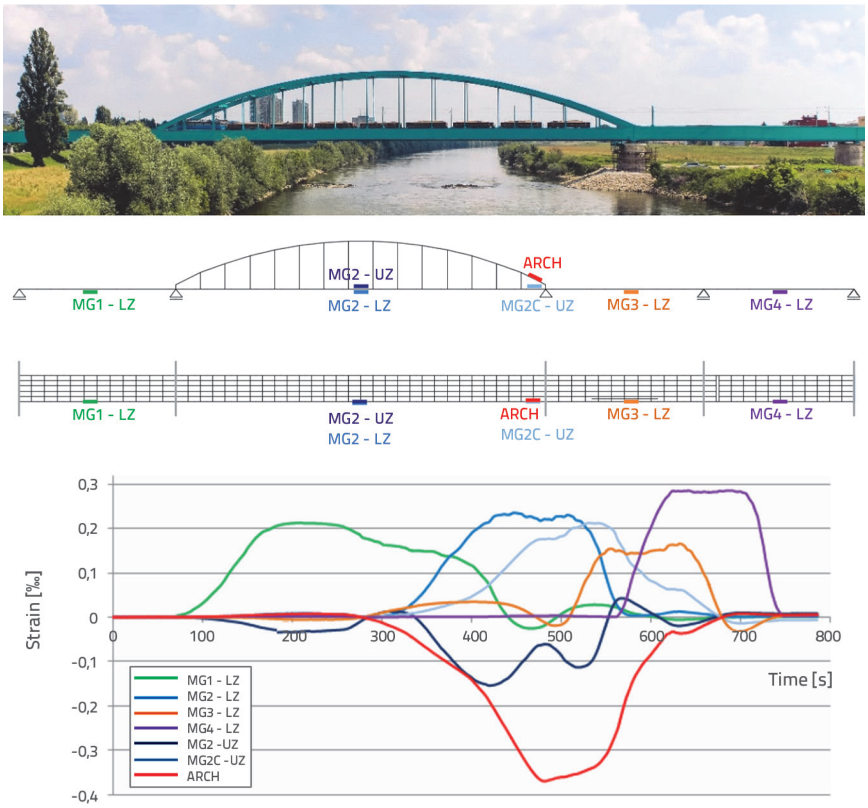

Figure 13. Measuring points and relative deformation records at the Sava rail bridge in Zagreb (measurements were made during passage of two trains with the total mass of 1437 tons, operating at the speed of 2 to 3 km/h) [30]

Figure 14. Crane-assisted installation of sensors on the viaduct situated at the Zagreb International Airport, and sensor installation from scaffold at the Slavonska – Radnička overpass in Zagreb

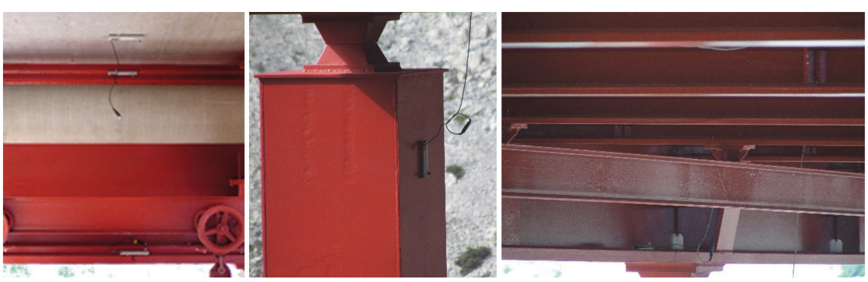

Figure 15. Relative-deformation measuring sensors on the Maslenica Bridge [31]

of bridge traffic, which causes not only direct costs but also significant indirect costs.

After construction and before opening to traffic, bridges are subjected to load testing. Such load tests are also conducted after bridge rehabilitation works, and may also be required after some emergency events (such as earthquakes) or in the case of extraordinary transport of the cargo that exceeds traffic load for which the bridge has been dimensioned. The most significant parameters measured during such load testing are: displacement of superstructure and abutments, and strains in the critical cross-section, i.e., in the zones where extreme values can be expected. Dynamic load measurements involve measurement of dynamic displacements, which are most frequently determined by integrating measured acceleration records. Figure 13 shows strain records measured at the superstructure of the Sava railway bridge in Zagreb during the passage of two trains with the total mass of 1437 tons, operating at the speed of 2-3 km/h.

Displacements are measured on the pavement structure, and on footways or inspection ways, i.e., on the parts of the bridge that are easily accessible. Geodetic survey instruments (levels, total stations and, in recent times, GPS devices) are used in these measurements. In the case of cable stay bridges or suspension bridges, it is necessary to check displacements at the top zones of pylons. As these zones are usually difficult to access, appropriate cranes must often be used. Strains are mostly measured from the bottom side of the superstructure using appropriate cranes or scaffolds, because the load bearing elements of the superstructure cannot be accessed from the top side of the superstructure as they are hidden under the layers of waterproofing, asphalt, footways, parapets, etc. Examples showing installation of sensors for measuring strains on the viaduct situated at the Zagreb International Airport, and on the viaduct across the Radnička street in Zagreb, are presented in Figure 14. Sensors installed on the Maslenica Bridge are shown in Figure 15. In the case of bridges with box cross sections, sensors for measuring strains can be placed inside the cross section but, if that is not the case, appropriate scaffolds or special cranes must be used.

When measuring strains, sensors must be connected to a data acquisition system, which in the case of big, large-span bridges can mean that hundreds and sometimes even kilometres of cables must be installed [32]. A similar problem occurs in vibration measurements, and especially during determination of dynamic parameters of the structure (experimental modal analysis), when measurement is performed on a great number of measuring points. Examples of experimentally determined natural vibrations and the corresponding natural frequencies are shown in Figure 16.

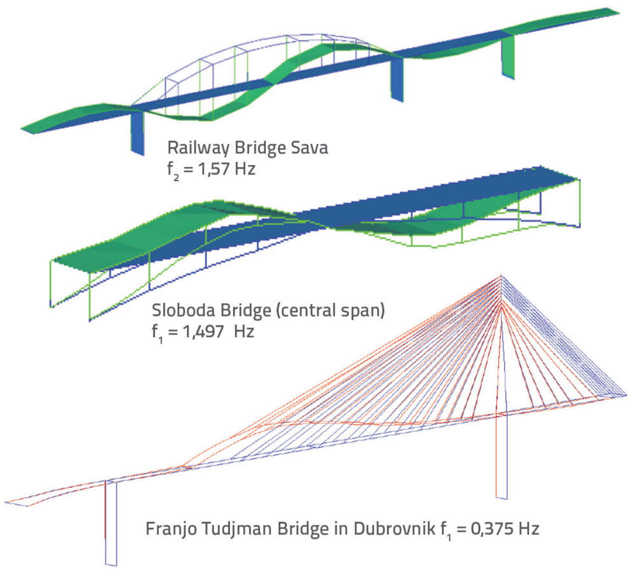

Figure 16. Experimentally defined natural vibrations and the corresponding natural frequencies [34-36]

The use of unmanned aerial vehicles will increase efficiency, reduce costs and speed-up investigation works and visual inspections on bridges [33]. Unmanned aerial vehicles can also potentially be used for installing sensors on hardly accessible locations, and the development of wireless sensors and data collection systems will additionally accelerate and simplify bridge testing activities.

3.2. Plan for the development of the autonomous system BePo

The measurement system, currently under development in the scope of the ASAP project, will enable visual inspection, crack detection and monitoring, sensor installation, and data collection to capture deformations and dynamic parameters of structures, all this to be integrated on an unmanned aerial vehicle. Measurement ranges and optimum positions of measuring devices will be determined within these development activities to enable simpler and faster displacement detection and/or relative deformations and dynamic parameters of structures by measuring ambient or artificially caused vibrations. Project activities also involve optimisation of measuring equipment for displacements and dynamic parameters, to fine tune this equipment for use in the autonomous robotic system, and for the automated data collection. The project aims to develop and realease an alpha–prototype of the unmanned aerial vehicle that will be able to carry the aforementioned sensors for measuring relative deformations and vibrations to inaccessible elements of the structure. The project activities can be divided into three groups:

Conceptualisation, development, and construction of the unmanned aerial vehicle body with mechanical elements that will enable placement of measuring instruments at specified positions. To that end, a mathematical model of the system is also being developed, with a particular emphasis on modelling the contact dynamics and its influence on the dynamic and aerodynamic properties of the unmanned aerial vehicle.

When developing a mathematical model of the system, a special emphasis will be placed on the analysis of stability, taking into account the hybrid properties of the dynamics of contact with the environment. This analysis will be considered when deriving the nonlinear control system with satisfactory adaptive robust properties that will ensure stability of the unmanned aerial vehicle during the flight and during the contact.

The third important feature of the alpha-prototype of the unmanned aerial vehicle involves an accurate localisation under given conditions. For this purpose and taking into account the payload capacity of the unmanned aerial vehicle, the vehicle will be equipped with necessary sensors (3D lasers, stereo cameras, RTK, GPS, etc.). Furthermore, considering the dynamic properties of the unmanned aerial vehicle, the synthesis of the UAV trajectory planning algorithms will be conducted, which will enable autonomous installation of measuring devices at predefined locations.

3.3. Challenges in the development of the autonomous system BePo

No robot is like a Swiss army knife, i.e. as a versatile tool that generally offers a lot of possibilities with poor results when it comes to practical use [37]. The reality is just the opposite: the development of robotic systems involves the development of specialized tools adapted to a particular usecase. A similar approach should also be adopted in the development of the autonomous system BePo, whose two uses can be reduced to the visual inspection of structures and the interaction with environment, i.e., installation of sensors onto the structure. Although the the systems are based on a standard rotorcraft structure with four rotors, the systems will be differentiated by the group of sensors and tool they utilise.

The basic problem to be resolved to make both systems autonomous is the localisation (positioning) in the global environmet and relative to the structure that is to be inspected. Unmanned aerial vehicles have become a very frequent tool for visual inspection of structures [38-40]. Currently the use of such aircrafts implies inspection with at least two operators, i.e., a pilot and a cameraman, who must manually perform inspection of the structure. Such systems have a certain level of autonomy, with pilots often controlling the UAV using a closed loop controller based on GPS measurements. GPS measurements are fused with other UAV sensors, such as: barometer sensors, inertial measurement units, and cameras. Such a system enables the pilot to set the waypoints in the GPS coordinate system, but relies on the pilot's experience and the cameraman's expertise

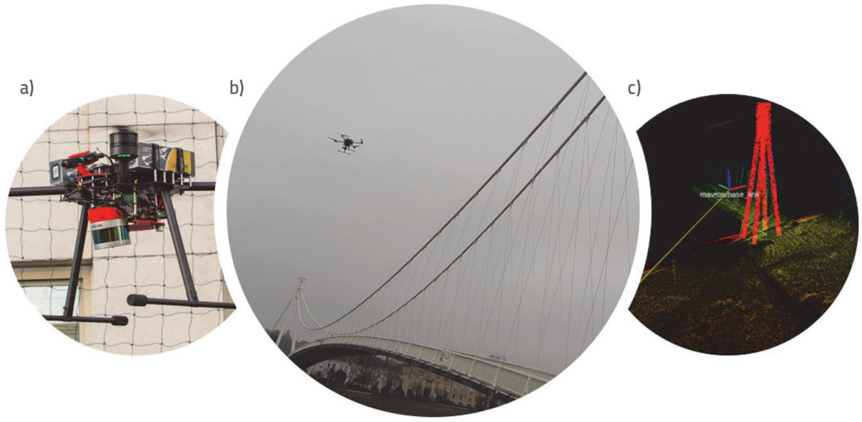

Figure 17. a) Autonomous system BePo for the in-flight surveying of structures; b) Survey of a pedestrian bridge in Osijek; c) Results showing correspondence of point clouds collected with 3D lidar, compared with pylon model (marked in red)

in order to to determine and set the distance from an object, i.e., to accurately survey the structure.

To transform the unmanned aerial vehicle into a fully autonomous system that is capable of surveying the entire structure without presence of the operator, the UAV must be equipped with additional sensors, 3D high-resolution laser beams (3D lidar), and cameras capable of sensing the depth of pixels in the image (RGBD). Moreover, it is also necessary to develop simultaneous localisation and mapping (SLAM) algorithms that will be capable of finding the correspondence between the point clouds registered with sensors and the 3D model of the structure. Such algorithms ensure the system is full autonomy during inspections and can be used in situations when the GPS signal is not available (under the bridges), i.e., when there are significant magnetic disturbances due to ferromagnetic material that is used in the construction. Comparison of the most frequently used localisation and mapping algorithms, with an emphasis on their use in unmanned aerial systems, shows that the use of this technology enables more accurate localisation of the aircraft compared to the standard GPS devices [41]. Of course, localisation is just the first step – it is also necessary to adequately link several point clouds and to accurately segment and recognise corresponding 3D elements of the structure. An example of the results obtained by using such algorithms during testing of a pedestrian bridge in Osijek is presented in Figure 17.

To establish the contact between the autonomous system BePo and the environment, we propose to equip the aircraft with additional sensors and actuators. Actual connection between the sensor and the environment will be made in two stages using two-component glue. In the first stage, the aircraft equipped with a diffuser applies the first component of the glue, after which the second aircraft, equipped with a manipulator with several degrees of freedom, attaches the sensor previously coated with the second component of the glue [42]. In order to establish a firm bond between the structure and the sensor, the autonomous system BePo must apply a controlled amount of force onto the structure. The amount of this force, and the contact duration are specified by the glue manufacturer. Standard approach used in

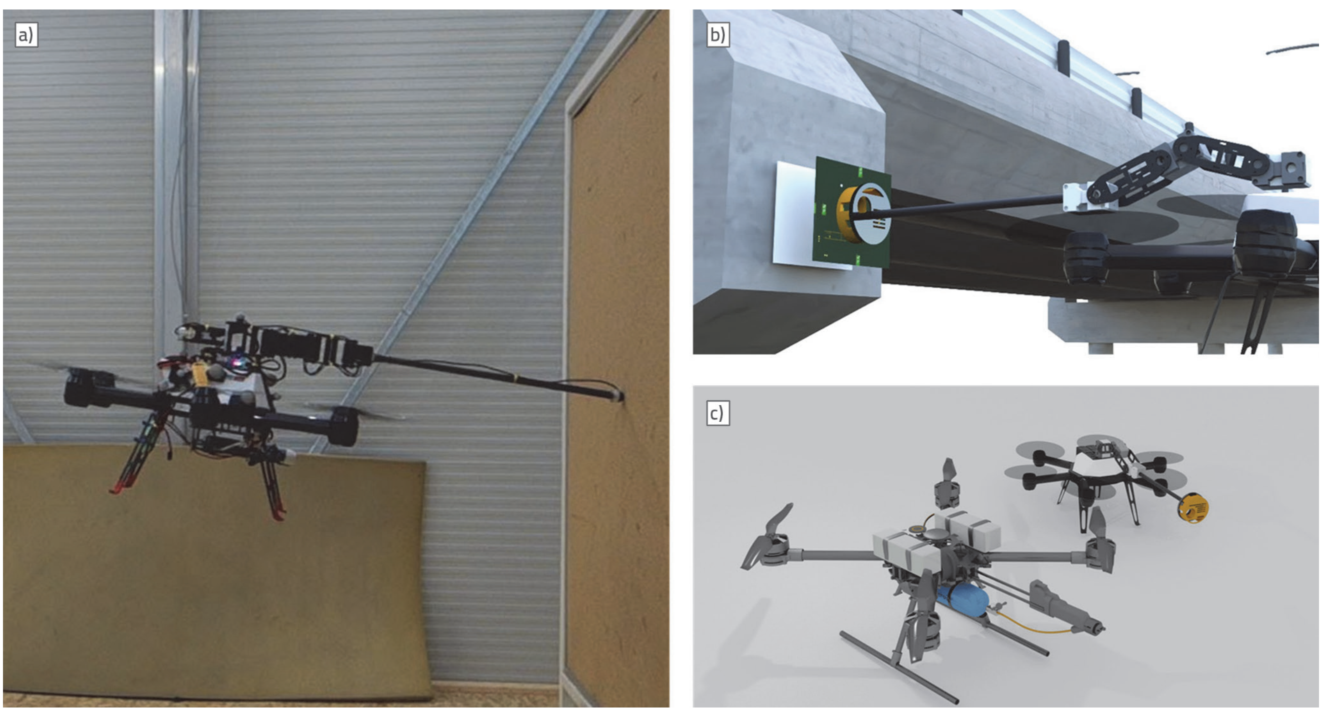

Figure 18. a) Unmanned aerial vehicle equipped with manipulator with several degrees of freedom during establishment of contact with the surface, using impedance control system through manipulator force; b) Imagined scenario for connecting sensor to the structure; c) use of heterogeneous robotic system

robotics for applying force onto a structure includes the synthesis of the force control system, based on the impedance filter derived for the manipulator position control loop. Such a system has been tested in laboratory conditions, and the results obtained are shown in [43]. Prior to the actual contact, it is necessary to accurately detect, using visual feedback, the position of the first glue component. The visual system for detecting the first component of the glue, will be incorporated in the existing method of localisation, through segmentation and overlapping of point clouds. This will enable a high level of accuracy during the sensor connection operation.

4. Conclusion

The initial idea of the ASAP project originates from the recognised problem and the need of the public and private sectors for a more efficient inspection of structures and for the application of inspection results in order to make more reliable decisions about the integrity of structures. The project has brought together prominent representatives from a number of engineering disciplines: civil engineering, robotics, and ICT, the aim being to develop a system for an autonomous conduct of experimental tests of materials and structures by means of a robot and an unmanned aerial vehicle, offering the possibility of wireless collection of data in real time. An overview of possibilities for developing such a complex system, including specific challenges in all disciplines involved in this development activity, is presented in the paper. Further development of the autonomous system ASAP also includes the linking of experimental testing results with numerical analyses to assess the serviceability and remaining bearing capacity of structures, as well as the data storage concept in the form of big data storage system destined for end users. The ASAP project introduces the fourth industrial revolution into the field of maintenance of structures. Considering a relatively slow introduction of advanced technologies into the construction sector, the interdisciplinary core team formed during the project can become a strong strategic partner to public and private sector operators, and thus a competitiveness cluster can jointly be formed in the field of modernisation of civil engineering. In addition to the scientific community involved in the ASAP project, indispensable participants in such a competitiveness cluster are certainly leading operators of the existing transport infrastructure of the Republic of Croatia, as well as small, medium-size, and large entrepreneurs who are involved in the assessment of the condition and bearing capacity of structures, in the development of equipment for structural inspections, in the development of intelligent robotic systems and, finally, in the development and implementation of computer platforms and applications for use in civil engineering.

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