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DOCTORAL PROGRAM IN ENVIRONMENTAL AND INFRASTRUCTURES ENGINEERING

The Doctorate in Environmental and Infrastructure Engineering has been operating since the academic year 2008/2009. The program introduces doctoral students to the world of research on key theoretical and technological elements associated with water, environment, hydraulic and transportation infrastructures, geology, as well as geomatics.

In this context, the program is grounded on environmental, civil, and industrial applications where water is the primary unifying element. The doctorate program is characterized by a strong inter- and multi-disciplinary structure and is organized according to the following key thematic areas.

1. *Hydraulic Engineering*, where major research themes include: fluid mechanics; fluid-structure interactions; hydraulic measurements; river hydraulics; sediment mechanics; hydraulic risk assessment and management; flow and transport processes in porous systems; hydraulic networks, hydro-energy; oil and gas development and applications.
2. *Hydrology, hydraulic structures, water resources and coastal engineering*, where the main research topics include: hydrology and water resources, with emphasis on the main physical processes of the hydrological cycle, water and energy budgets; hydrogeological hazard and mitigation strategies, including hydrological extremes, floods, droughts and precipitation, early warning operative systems, snow avalanching and flood risk; hydraulic networks engineering; and coastal engineering.
3. *Environmental technologies*, with focus on: water supply technology and treatment, (including disposal / reuse of wastewater, sludge management and disposal, anaerobic digestion processes); management and planning of environmental resources (including water quality modelling, knowledge-based decision support systems); solid wastes and sludge management; phenomenology of the atmospheric environment and treatment of gaseous emissions; contaminated soils and their remediation.
4. *Transport infrastructures and geology*, with focus on: transport networks, including functional interactions with regional, national and international territory; sustainable development, in terms of dynamics of development and its relations with the infrastructure system; technological innovation, including methods and indicators for performance characterization of infrastructure construction and maintenance techniques; hydrogeological risk, landslide hazard; water resources identification and management, pollution problems.
5. *Geomatics*, with focus on: physical geodesy and satellite geodesy; positioning and navigation; surface surveying with optical or other sensors, such as SAR, LIDAR; digital photogrammetry and image analysis; remote sensing; geographic information systems; cultural heritage reconstruction and archiving.

The curriculum of PhD students has been tailored to the general and specific research questions associated with the multifaceted interactions between the water sphere and the key evolving anthropogenic activities responding to the needs of modern society.

Career perspectives include opportunities at Universities, Research Centers, public bodies and Authorities, as well as private companies / industry. Small and medium size enterprises (SMEs) which cannot afford the development of an in-house specific know-how program may also require such highly professional profiles to guarantee critical innovation and competitiveness.

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LOW COST AERIAL PHOTOGRAMMETRY IN ARCHAEOLOGY

Martina Ballarin - Supervisor: **Prof. Francesco Guerra**

The last few years have seen an exponential growth in the use of UAV photogrammetry. This evolution has opened new possibilities and new scenarios for close range surveying, due to the combination of aerial and terrestrial techniques and relatively low-costs compared with traditional aerial techniques.
The growing use of software for extracting point clouds from non-oriented images has obtained great attention not just from the "geomatic" scientific community, but also by users from other disciplines including archaeologists. It is easy to understand this success: the various software packages combine high quality results, both in qualitative and quantitative terms, with ease of use. The spread of these products also coexists with a growth in the market of low cost off-the-shelf cameras, able to acquire high quality and high-resolution images.
The research developed during the three years of my PhD focused on the use of micro UAVs for close range photogrammetry. Though a number of case studies carried out in the Laboratory of Photogrammetry of IUAV University, I used and analysed many different configurations of these systems, regarding both the type of cameras used and the type of vehicles on which the cameras were mounted. The techniques were used in different fields and on objects with different morphologies, from the archaeological survey to the survey of Cultural Heritage more generally.
From the experiences gained during these years, and after the development of amateur aerial vehicles on one side and lighter cameras on the other, the research began to focus on the analysis of the potentials of a system integrating those two components in the archaeological field. In this field economic considerations are often an issue and the metric aspect of the data is frequently subordinated to its interpretative value.
The use of "action cameras" for photogrammetric purposes has had a slow development because the images acquired by the first sensors had a quality and resolution that were insufficient to obtain the accuracies of a photogrammetric survey. Nowadays, however, compact cameras can acquire high-resolution images even in extreme activities, such as free fall, underwater swimming and diving.
This thesis is concerned with testing these cameras and the analysis of the results they can achieve: in particular we analysed the Go Pro Hero3 Black Edition (fig. 1). This camera allows the acquisition of images up to a resolution of 12MP (4000x3000) and its weight and dimensions (76 g – camera with battery - 60x40x20 mm) allow them to be mounted on non-professional aerial vehicles, such as the Parrot Ar.Drone 2.0 (fig 2). These vehicles are made for recreational purposes and for this reason are cheap and easy to pilot as they can be controlled via tablet or smartphone through specific applications. In this way, we are able to obtain a low cost easy-to-use system, suitable for archaeologists and for archaeological documentation.

1: Go Pro Hero 3 Black Edition.

The main limit of this system is the fact that the photograms acquired by these cameras have a great level of distortion and consequently raise problems in the calibration process. During my research I performed a number of tests using different software products (free, low-cost and implemented ad hoc) and different methodologies (test field calibration; self calibration) to calculate the interior parameters of the camera. I also performed a number of tests to analyse the whole acquisition system and test the accuracy of the results we could reach on different typologies of objects and with different network geometries.

2: Parrot Ar.Drone 2.0.

After this first phase, this system was used during an intensive surveying campaign in an archaeological site in Molise, the ancient city of Altilia. Here, we performed a number of acquisitions on different objects and following different workflows. The data obtained was compared with that acquired through more traditional close range photogrammetric systems (calibration cameras on professional drones) and/or a laser scanner.
In this phase, the system proposed was used in different modes: the vehicle was flown manually, while another operator controlled the capturing on the GoPro App, or with automatic flight, using the GPS module "Flight Recorder" and setting the GoPro in time lapse.
In addition we chose different morphologies of monuments: 3D objects (Porta Benevento); bi-dimensional objects (the forum of the city) and 2.5D objects (the shops at the side of the *decumanus*; the sanctuary of San Pietro di Cantoni). The Ground Control Points were acquired through an RTK GPS survey (centimetric precision), using both natural points on the architectures or specific checkerboard targets.
The results obtained (fig 3) were compared to those acquired by well-established techniques. I analysed all the possible products achievable: surface models; point clouds; 3D coordinates of some checkpoints on the models and 2D coordinates of checkpoints on the ortophotos.
A large variety of different acquisition techniques were compared through the different case studies, in order to fully comprehend the possibilities of the methodology proposed here.

3: One of the possible results obtained through this system. The orthophoto of San Pietro di Cantoni.

LARGE-EDDY SIMULATION: A TOOL TO STUDY LAND-ATMOSPHERE INTERACTIONS

Giulia Ercolani - Supervisor: **Prof. Marco Mancini -** Co-supervisor: **Dr. Chiara Corbari**

Large-Eddy Simulation (LES) has been recognized to be a valuable tool for reproducing Atmospheric Boundary Layer (ABL) turbulence since the 1970s. The initial applications of LES to ABL modelling considered almost exclusively idealized regimes, namely homogeneous surfaces properties, prescribed fluxes at the ground and periodicity at the lateral boundaries. In addition, these initial applications were confined into purely atmospheric or fluid dynamics research. But the continuous increase in computational capabilities has led to LES of more complex ABL flows, that overcome the above-said idealized constraints. In particular grid nesting techniques are used to relate microscale turbulence with the larger-scale flow, and the coupling of LES with a Land-Surface Model (LSM) allows to dynamically compute surface fluxes during the simulation, and therefore to reproduce the feedback existing between the land surface and the atmosphere. In this context Numerical Weather Prediction-Limited Area Models (NWP-LAMs) appear to be particularly attractive tools to perform LES of the ABL, because natively supplied with the capability of nesting and with the equations of motion coupled with a LSM. Moreover, in recent years computational capabilities have reached the level that makes affordable the cost ABL LES even with standard resources at disposal. Consequently, LES of the ABL is becoming a widespread tool of investigation in several fields not traditionally linked to Large-Eddy Simulation, such as hydrology, renewable energy production, agrometeorology and others.
In particular, in the hydrological context the interest in LES of the ABL is mainly oriented to land-atmosphere interactions, and therefore to coupled LES-LSM. In fact surface fluxes of sensible and latent heat, that are the expression of the land-atmosphere interaction, are two fundamental terms of the hydrological balance. Consequently their accurate estimation is of great importance in water resources management at both the regional or basin scale and the field scale. For instance, coupled LES-LSM can be employed to assess surface heterogeneity impact on ABL structure and evolution, and in turn on surface turbulent fluxes, to quantify the importance of the land-atmosphere feedback on the estimation of the fluxes themselves, and also to support the interpretation of turbulent fluxes field measurements.
The thesis explores the capabilities of the mesoscale model RAMS in performing LES of the ABL and then employs it to quantify the impact of meteorological forcings spatial distribution on a water and energy balance model. In fact RAMS may be considered a suitable instrument for hydrologically-oriented applications, since its equations of motion are natively coupled with a LSM.
But RAMS is originally designed to simulate mesoscale flows, and therefore an evaluation of its performances in reproducing microscale turbulence is needed to obtain valuable results. Moreover, the complexity of the coupled modelling system, combined with its diffusion to fields not traditionally linked to LES, reinforces the importance of an extensive investigation of the code capabilities under various conditions and with different setups.
The first part of the thesis is dedicated to the analysis of the code when employed in idealized neutral and free convection regimes. It is proved that RAMS is actually a suitable instrument to perform LES of the ABL in both the previous conditions. Furthermore, an adequate turbulence reconstruction has been obtained with an affordable computational load. The analysis has focused on the impact that the computational grid has on the results, since in this code grid spacing implicitly determines the filtering of the LES. Guidelines have been obtained for grid design in LES of the ABL under both convective and neutral regimes. A key role has been identified for cell aspect ratio (horizontal over vertical resolution) in terms of quality of turbulence reconstruction. Namely the best results do not correspond simply to the finest affordable horizontal and vertical resolutions, but an optimal ratio between them must be maintained. Different values of the minimum horizontal resolution and of the optimal cell aspect ratio have been found for convective and neutral regimes.
RAMS-LES has been also tested in reproducing a real diurnal cycle of the ABL over a heterogeneous surface, in this case coupled with its land-surface model LEAF-3. The coupled model predictions have shown a good agreement with observations. In particular, excellent results have been obtained for net radiation and sensible heat flux, and a general good match for the other surface quantities (latent and soil heat flux, air temperature and humidity) has been found. A qualitatively correct time evolution of mean vertical profiles has been assessed. Therefore, it has been demonstrated that the coupled model can properly simulate a diurnal cycle of the ABL and of land-atmosphere interactions in real conditions.
The analysis concerning RAMS-LES capabilities and the factors affecting them has continued with the evaluation of the impact that surface heterogeneity level of description has on the coupled model results. It has been found that the predictions of surface quantities (e.g. surface turbulent fluxes, land temperature etc) significantly differs from the reference as the level of aggregation of the heterogeneity approaches the patches size. The differences increase as the surface parameters resolution coarsens. Instead, ABL turbulence has shown non-negligible differences even at scales that still reproduce almost correctly the surface heterogeneity. At the same time larger scales of aggregation produce results that are more similar to the reference than those corresponding to a more detailed description of the heterogeneity. But, when the scale exceeds the ABL height, the impact of a more organized turbulence appears.
After the extensive assessment of RAMS-LES capabilities, the results of a coupled LES-LSM in real conditions have been used to evaluate the role of the meteorological forcings microscale spatial distribution in a water and energy balance model. Different responses have been detected for turbulent fluxes and for land surface temperature, and it has been found that soil moisture regulates the impact on sensible and latent heat fluxes. Moreover the analysis seems to suggest that the water and energy balance model attenuates the errors when passing from forcings to results, but the spatial pattern of the input distortions is generally still recognizable in the outputs. Therefore, the spatial interpolation of punctual measurements of the meteorological data is important if an accurate simulation is desired. In this context we have proposed and tested an alternative method to interpolates observations at the microscale. It is based on surface properties and not on physical distances as the standard IDW scheme, since at the microscale the complexity of meteorological fields is mainly related to surface heterogeneity, since large atmospheric conditions are the same. The analysis has shown that it actually performs better than the IDW method in presence of a fragmented surface heterogeneity, i.e. with a variability not organized into homogeneous macro-areas.

THE IMPACT OF SPACE-TIME ADAPTATION TECHNIQUE ON SOLUTE TRANSPORT MODELING IN POROUS MEDIA

Bahman Esfandiar Jahromi - Supervisor: **Prof. Alberto Guadagnini**

Co-supervisors: **Prof. Simona Perotto, Dr. Giovanni Porta**

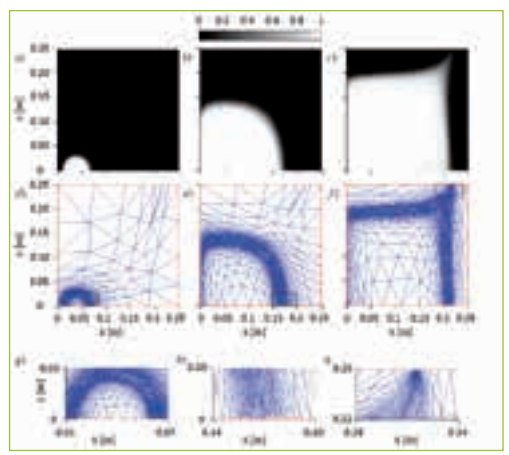
A wide set of physical processes involves transport of solutes in porous media. These include contamination of groundwater by inorganic and organic chemicals, petroleum generation and migration, reactive processes which can modify the properties of soil and rock formation. Transport of solute mass in the subsurface is due to advection and diffusion processes, taking place at the pore level. Due to the practical infeasibility to model pore-scale transport at typical laboratory and field scales, solute transport in porous media is typically described by means of effective models. A standard choice is to adopt a continuum-based representation of the process based on the standard advection-dispersion equation (ADE). The basic assumption underlying the ADE is that the dispersion coefficient can be described by the sum of effective diffusion and hydrodynamic dispersion, according to the so-called Fickian analogy. The advective term results from a velocity field, which is typically assumed to obey Darcy's law. In practical applications, numerical approximation methodologies are demanded to compute the evolution of the concentration in the space-time domain of interest. Independently of the employed methodology, the results of numerical simulations are unavoidably subject to an approximation error, which is related to the selected discretization scheme. For instance, the computational error associated with Eulerian discretization methods (e.g., finite elements, finite volumes and finite differences) is a function of the spatial grid and of the time step size used for the discretization. To this end, the first aim of this thesis is the development of a two dimensional finite element model combined with a space-time grid adaptation procedure to improve the accuracy of solute transport modeling in porous media. We employ the ADE for the interpretation of non-reactive transport experiments in laboratory-scale porous media. When compared with a numerical approximation based on a fixed space-time discretization, the proposed approach is grounded on a joint automatic selection of the spatial grid and at the time step to capture the main space and time system dynamics. The space adaptive process is driven by a suitable anisotropic recovery-based error estimator which enables us to properly select the size, shape and orientation of the mesh elements. The adaptation of the time step is performed through an ad-hoc local reconstruction of the time derivative of the solution in the spirit of a recovery procedure as well.

Macro-scale models, including the ADE, entail the definition of effective transport parameters, which are typically assumed to be linked to the porous media geometry. In laboratory and field scale applications these parameters are generally unknown, and need to be estimated by means of inverse modeling procedures. To this aim, multiple evaluations of the selected model are typically needed. This can be computationally costly. Therefore, as second objective of this work, we quantify the impact of the implementation of the space-time adaptive procedure on parameter estimation and uncertainty quantification. The model calibration is performed in a Maximum Likelihood (ML) framework upon relying on the representation of the ADE solution through a generalized Polynomial Chaos Expansion (gPCE).

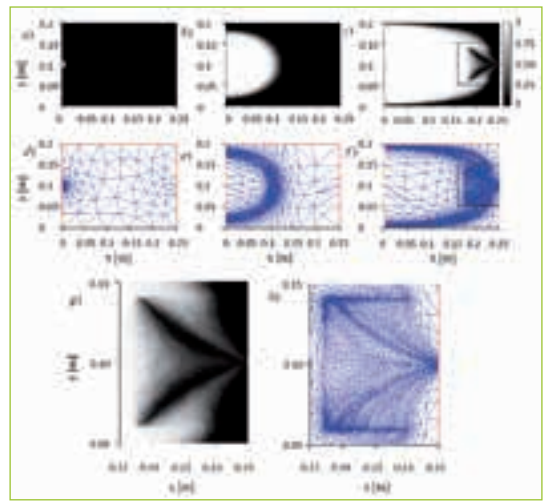
The whole proposed methodology is assessed through two-dimensional numerical tests. First a numerical convergence analysis of the spatial mesh adaptivity is performed by considering a test-case with analytical solution. Then, we validate the space-time adaptive procedure by reproducing a set of experimental observations associated with solute transport in a homogeneous and blockwise heterogeneous sand pack. The impact of the space-time adaptation methodology on the capability to estimate the key parameters of an ADE model is also assessed on the basis of experimental solute breakthrough data measurements for both homogeneous and blockwise heterogeneous sand packs.

These assessments show that the space-time adaptation methodology is robust and reliable. In particular, it allows us to obtain a significant improvement of the simulation quality of the early solute arrival times at the outlet of the medium. Moreover, the proposed adaptation methodology leads to ML parameter estimates and model results of markedly improved quality when compared to classical inversion approaches based on a uniform space-time discretization. Our results suggest that the implementation of a space-time adaptive methodology has a considerable impact on global analysis and uncertainty quantification procedures. In particular, it allows understanding the influence of input uncertain parameter on the model output.

Further extensions of this work may involve solute transport modeling in complex heterogeneous fields as well as field-scale data interpretation. Investigation of the impact of space-time adaptation in the presence of chemical reactions is another possible and challenging application of interest.



1: Experimental flow cell; homogeneous sand pack: solute concentration field a)-c); associated anisotropic adapted mesh d)-f); details of the adapted mesh g)-i) for t = 100s (left), t = 1, 500s (center), t = 3, 000s (right)



2: Experimental flow cell; heterogeneous sand pack for t = 5s (left), t = 7, 50s (center), t = 1, 900s (right): a)-c) solute concentration field; d)-f) associated anisotropic adapted mesh; g)-h) details of low permeable block

MATERIALS RECOVERY FROM WASTE LIQUID CRYSTALS DISPLAYS: A FOCUS ON INDIUM

Federica Forte - Supervisor: **Prof. Ing. Mario Grosso**
Assistant supervisor: **Dr. Danilo Fontana**

Liquid crystal displays (LCDs) are becoming more and more widespread in electronic applications and they are definitely replacing the old cathode ray tube devices in TVs and monitors. Due to the presence of hazardous components, that require adequate treatment and disposal operations, and to the relatively high content of critical raw materials that can be recovered, treatment of waste LCDs has been gaining increasing attention among the scientific community in recent years. In Europe waste LCDs are fed into a separate recycling process after collection. Treatment process generally consists in a disassembly step aimed at removing the hazardous components and the valuable ones for further treatment and recovery; whilst for some components separated after primary dismantling (metallic fractions and metal rich-components such as printed circuit boards and cables) the recovery paths are quite well established, some others, such as the LCD glass panel, require further investigation. The LCD panels are currently stocked at the plant or incinerated, since no recycling process is available yet at the industrial scale; this practice obviously leads to a loss of resources potentially recoverable, such as the critical metal indium as well as the glass fraction and the polarizing films. Indium, in particular, present in the LCD panel as indium tin oxide layer (ITO, i.e. indium tin oxide), has been recently included in a list of "critical raw materials" by the European Commission and its recovery from secondary sources is gaining increasing attention among the scientific community. In the last decade a number of works have been focusing on indium recovery from end-of-life LCDs. In most cases thermal treatment at high temperature was employed for the removal of the polarizing film, which implies energy consumption and potentially harmful atmospheric emissions. Indium recovery from the glass substrate is generally performed by hydrometallurgical techniques, consisting in a leaching step aimed at dissolving the metals of interests, followed by a separation step. The leaching is often carried out by employing acid mixtures with inhomogeneous concentration values, so that a comparison among the lixiviants (in terms of leaching efficiency) is not always straightforward. Moreover, a shredding step is often performed before the leaching; in same cases it is carried out on the glass substrate obtained after the removal of the polarizing film in other cases on the entire LCD module. Indium recovery from the aqueous phase is then generally performed through solvent extraction. Solvent extraction (or liquid-liquid extraction) has been widely used in the past as a concentration and separation technique due to its characteristics of high selectivity and high recovery efficiency. However, organic extractants such as D2EHPA, TBP, Cyanex 272 and Cyanex 923 diluted in organic diluents (such as kerosene, toluene etc.) are often employed, which are potentially hazardous for human health and the environment since they are responsible for VOCs emissions into the atmosphere.

The aim of this research project is to develop a hydrometallurgical technique to recover valuable materials from waste LCDs. The first step of the recovery process here proposed is aimed at removing the polarizing film from the glass substrate. Different treatment options were tested, such as thermal and chemical ones. Thermal treatments were performed both at high (T=100-240°C, 20°C/h) and at low temperature, the latter by employing liquid nitrogen (T = -196°C). Chemical treatments were carried out by soaking the waste LCDs into a number of organic solvents such as acetone, limonene, ethyl acetate and isopropyl alcohol; the influence of the ultrasound treatment was also investigated. The best results were achieved by liquid nitrogen, since approximately 20 minutes were sufficient to remove the polarizing film completely; moreover, the obtained product did not show significant degradation.

The second step of the recovery process is the leaching (or solid/liquid extraction), aimed at dissolving the valuable metals from the glass substrate. In order to evaluate the best operative conditions, a number of leaching tests were performed on a pure reagent (indium tin oxide, -325 mesh, ≥99.99% trace metals basis, Sigma Aldrich) by varying the leaching agent, the contact time and the liquid/solid ratio (L/S). The best results were achieved by employing HCl 6N as a lixiviant, since in a relatively short time (6h) ~90% indium was extracted. The operative conditions thus defined (HCl 6N, t=6h) were then employed for the leaching of the LCD glass substrate, i.e. the solid residue obtained after the removal of the polarizing film with liquid nitrogen.

Indium recovery from the aqueous phase was then investigated through solvent extraction with aqueous biphasic systems (ABSs), which are now gradually emerging as an environmentally-sound alternative to the classical "oil-water" extraction systems due to their characteristics of low cost, reduced flammability and reduced toxicity.

Indium extraction tests in an aqueous biphasic system PEG-ammonium sulfate-water were performed as a function of PEG concentration, salt concentration and molecular weight of PEG (PEG 3,350 and PEG 10,000), using 1,10 phenanthroline as a ligand. Experimental data showed that indium partitioning between the bottom and the top phase is quite independent from the composition of the system, since 80-90% indium is extracted in the bottom phase and 10-20% in the top phase. By increasing PEG concentration, the ratio between the bottom and the top phase volume decreases; since the percentage of indium extracted in the bottom phase is invariable, this leads to a concentration of the species of interest. Indium extraction is quite similar by employing PEG 3,350 as well as PEG 10,000, however the volume ratio decrease is more significant if PEG 3,350 is employed (in correspondence of [PEG]=18% w/w, the ratio between the bottom and the top phase volume is ~1.1). Further extraction tests should be performed on the leachate (i.e. the aqueous phase coming from the leaching of the glass substrate with HCl 6N) in order to verify the selectivity of the recovery technique compared to other ions (mainly tin).

DEVELOPMENT AND TEST OF A MULTI-SENSOR UNMANNED AIRCRAFT SYSTEM FOR ENVIRONMENTAL SURVEYS

Rossana Gini - Supervisor: **Dr. Giovanna Sona**

In the past the Unmanned Aircraft Systems (UAS) development was driven only by the military market, thanks to their ability to perform the so-called "dull, dirty and/or dangerous" tasks. Nowadays, the appellation of the three D is going to be replaced by a new one, namely the three P of "precision, proximity and periodic": these adjectives refer to the low-altitude and periodic UAS flights which allow the acquisition of hyperspatial, precise and proximal data. Furthermore, the low cost of platforms and GNSS/INS systems together with the variety of available sensors make the UAS suitable to be employed in all the situations where a traditional vehicle (i.e. airplane) would be too expensive to justify its use.
In the last few years the UAS have been successfully introduced also in the Photogrammetry and Remote Sensing fields, but some investigations are still needed to establish specific processing methodologies: indeed, a pure photogrammetric approach has often trouble with UAS blocks, because of the presence of non-nadir images, scale differences, illumination changes, vehicle attitude fluctuations within the strip, etc. Hence, 3D modelling software packages are emerging from the Computer Vision community: they enable an almost fully automated data processing but lacking in intermediate quality control checks.
UAS equipped with GNSS/INS systems and digital cameras have become an interesting subject of research also in the Remote Sensing community. Indeed, their capability to generate hyperspatial resolution imagery at highly flexible temporal scales makes the UAS suitable to fill the gap between finer scale field samples and coarser scale satellite or aerial imagery. Despite that, developing vegetation maps from UAS imagery presents certain challenges: the spatial resolution is very high but the spectral and radiometric ones obtained from the low-cost compact cameras are relatively low, and the Red, Green and Blue bands are highly correlated.
Therefore, it is still necessary to develop appropriate Photogrammetry and Remote Sensing methodologies, by testing the potentialities of the different systems and assessing the accuracies of the final products.
Embedded in this context, the present dissertation focused on the development and test of a multi-sensor UAS system for performing environmental surveys. Before buying platform and sensors, the Politecnico di Milano group (Geomatics and Geodesy section of DICA) decided to exploit some collaborations, in order to acquire basic expertise in the practical use of UAS as well as in the processing of such imagery.
In the first investigation, a quadrotor Microdrones™ md4-200 was equipped with two compact cameras to collect RGB and Near-Infrared (NIR) images, which were analysed from both photogrammetric and photo-interpretation points of view. This experience proved that commercial photogrammetric software packages, like PhotoModeler and LPS, were able to perform the triangulation of non-conventional imagery. Then, classification of tree species was accomplished on a multispectral layer stack, generated thanks to the co-registration of RGB and NIR orthophotos through the projection on a common Digital Surface Model (DSM). In addition, some synthetic bands were produced to improve the classification results, like the Normalised Difference Vegetation Index and the Intensity, Hue, Saturation (IHS) channels. Even though the target species (a non-native invasive plant) was only partly recognised by the Maximum Likelihood algorithm, this pilot study demonstrated that low-cost sensors mounted on mini UAS have potentialities to be employed in sustainable forestry and agriculture monitoring and mapping.
The second experiment was performed with a fixed-wing Swinglet CAM equipped with an integrated RGB camera: this time, the purpose was the comparison between the pipelines of photogrammetric and Computer Vision-based software. Analyses on bundle block adjustments and on the final products (DSMs and orthophotos) were carried out: the Computer Vision-based software Agisoft PhotoScan was able to obtain good results by means of a fast processing, with few inputs from the user. On the contrary, photogrammetric software like PhotoModeler and LPS obtained better results in terms of Root Mean Square Errors of Check Points residuals, but with more user effort. In addition, Agisoft PhotoScan demonstrated to be able to well model buildings, flat and shadowed areas, and it created orthophotos with a high quality level.
After these first investigations, a multi-sensor UAS was developed by buying a low-cost HexaKopter by MikroKopter and two sensors: a compact digital RGB camera Nikon 1 J1 and a Colour Infrared (CIR) Tetracam ADC Lite. Different applications were carried out with this UAS: in this dissertation, three exemplifying case studies were chosen and described.
In the first experiment, the UAS acquired imagery of an ancient farmstead: the good level of detail of the RGB orthophoto (Agisoft PhotoScan) allowed the visual inspection of the roofs as well as the structural integrity analysis of the shingles.
In another survey, the HexaKopter and the Nikon 1 J1 flew over a mineral aggregate deposit with the aim of assessing its volume. The processing pipelines of Agisoft PhotoScan, PhotoModeler and some in-house photogrammetric programs (developed by University of Parma) were tested and compared: once again, the Agisoft PhotoScan performance was satisfactory not only in the bundle block adjustment but also in the modelling phase, producing a complete and smooth DSM. Agisoft PhotoScan results seem trustworthy but a reference volume value of the mineral deposit will be acquired to enable more reliable comparisons and estimates.
In the third case study, both cameras were used to acquire imagery of a nursery and perform tree species classification. A multi-temporal analysis was accomplished by flying in summer and in autumn, and a bi-temporal band ratio was computed in order to exploit any phenological differences of the eleven plants selected as classes. Different synthetic bands were derived, like vegetation indices, IHS channels and texture measures, thanks to the employment of the original RGB and CIR bands of the orthophotos created in Agisoft PhotoScan. At present, only few studies have been already made on incorporation of texture to classify tree species on hyperspatial UAS imagery, but none has used at the same time a pixel-based classification approach and multi-temporal bands. Hence, it was tried and tested a new workflow which relies on standard Remote Sensing methods: for instance, the texture analysis followed an approach already performed on very high resolution satellite imagery, by selecting the best window sizes of the Grey Level Co-occurrence Matrix and the best texture features. The concurrent use of texture and multispectral channels actually improved the Maximum Likelihood classification overall accuracy. The same result came from the multi-temporal images, whilst the IHS transformation (carried out to reduce the correlation between RGB bands) did not lead to a classification improvement.
In conclusion, this dissertation showed that the developed multi-sensor UAS demonstrated great potentialities: indeed, despite the limited payload and power endurance, its flexibility allowed the achievement of good results in different applications. Future outlooks may be the improvement of the on-board GNSS/INS system accuracy to enable direct photogrammetry, and further analyses related to the classification workflow: indeed, some of its steps may be better exploited for improving the tree species classification.
Lastly, hypertemporal monitoring may be possible (at least on small areas) by means of micro UAS, compact cameras and Agisoft PhotoScan by achieving good geometrical accuracies in short time. Obviously, more investigations are needed in this direction before such a workflow may be considered well-established.

MULTISCALE INVESTIGATION ON COLD FOAMED BITUMEN MIXES WITH RECLAIMED ASPHALT PAVEMENT

Gilberto Martínez-Arguelles - Supervisor: **Filippo Giustozzi**

Keeping roads in good condition requires regular maintenance activities; such maintenance requires a massive amount of non-renewable resources, mainly virgin aggregates, given the large extent of the road networks. Besides, standard maintenance and rehabilitation activities create delays for users, traffic capacity deficiencies, and safety issues for construction site workers and drivers; on the other hand, it demands a large amount of virgin material handling and equipment. The economic crisis, increased costs of materials, and a strong desire to maintain a safe, efficient, and sustainable roadway system have fueled a resurgence of recycling existing pavement as a primary option.

The practice of limiting the disposal of old pavement materials is well known by minimizing the use and transport of virgin aggregates as well as reducing land filling; it also lowers environmental impact. These benefits, combined with the lower temperatures used in asphalt recycling, might lead to the belief that recycling always represents an eco-effective strategy. However, producing asphalt mixes at lower temperatures represents a successful alternative only if the final pavement is capable of competing, in terms of durability for instance, with standard hot-mixes. Also, the environmental effects of foaming agents or additives, if used, have to be as low as possible to achieve good results in the Life Cycle Assessment (LCA) of the product.

Different techniques are currently being used to recycle existing pavements. One of the most adopted is based on foamed bitumen mixes. Foamed bitumen is produced when hot bitumen, cold water, and air are mixed under pressure in an expansion chamber. Sometimes a foam additive is added to improve the quality and stability of the foam. Spraying simultaneously hot bitumen (normally between 150°C and 180°C) and water (ambient temperature) causes the mix to expand several times its original volume generating a fine mist or foam. The physical properties of this "new binder" are altered temporarily (seconds), for example, viscosity and surface tension of the bitumen are reduced significantly allowing the binder to coat partially the aggregates during the mixing process. Foamed bitumen mixes are mostly applied by European countries as a cost-effective replacement for base and sub-base layers; full-depth recycling and cold-in-place methodologies are generally considered hard to implement on upper surface layers due to high inhomogeneity of the existing paved materials (e.g., different age of the sections to be recycled, dimension and shape of aggregates, binder content, oxidation of binder, etc.) even for relatively small areas. Moreover, it is generally agreed that cold-recycled mixes end up being a cost-effective method but with inferior long-term performance with respect to hot-mixes. Nevertheless, despite significant advancements in the last decade, the adoption of foamed bitumen still relies substantially on empirical trials and lacks universally accepted mix-design procedures. Several aspects concerning the effect of bitumen grade, source, and chemical composition on foaming properties are not yet fully understood. Analogously, the impact and influence of these characteristics require more research in order to truly identify bitumen and foamed bitumen characteristic governing mechanical performance of foamed bitumen mixes (FBM). Road industry offers interesting alternatives such as fiber reinforcement, that have been successfully tested on hot mix asphalt, opening new windows for enhancing mechanical properties of FBM. Another key issue is the analysis of full scale performance of pavements with foamed bitumen applications.

This doctoral study employed a Multiscale approach analyzing the foamed bitumen and foamed bitumen mixes from different performance scale (micro-scale, macro-scale and full-scale) by means of advanced laboratory research technics and assessing bitumen fundamental properties; physical, rheological, chemical, microscopic. The mix design process, as well as, the study of the mechanical properties of foamed bitumen mixes were also investigated.

In addition, the effect of different bitumens sourced on the foaming characteristic was addressed as well as the impact of a commercial foaming additive on the fundamental bitumen properties. The influence of the bitumen sourced, foaming additive and foaming characteristic was then investigated on the mechanical behavior of foamed bitumen mixes considering three foamed bitumen contents. A number of different foamed bitumen mixes were manufactured involving two types of synthetic fiber reinforcements at three different fiber contents. A select group of mixes involved Portland cement as active filler. A novel curing process has been proposed. The advantages of the novel method involves the inclusion of a vacuum system device during the mixes' curing process in laboratory, which may reduce the possible aging process on the samples by the extraction of the oxygen and accelerate the water extraction on the cylindrical specimens.

The full scale investigation involved the analysis of the performance of several trial sections with foamed bitumen mixes in the State of Virginia. Performance data analyzed involved functional and structural parameters with service time between 4 and 7 years.

The approach of the research together with the experimental program allowed holistic understanding on the performance and factor affecting foamed bitumen and foamed bitumen mixes. The influence of the foaming process on the bitumen fundamental properties, as well as the effect of bitumen source, bitumen grade on the foaming properties was identified. Fundamental properties as viscosity and chemical analysis (Differential scanning calorimetry) revealed better understanding and correspondence with foaming properties. The addition of FA had very little effect on the mechanical performance with respect to mixes with the same bitumen but without FA. The FR inclusion resulted in increased dynamic modulus at some temperatures. Portland cement used as active filler provided significant increments in both moduli and strength, although the greater benefits are observed in moisture resistance.

The full scale investigation on trial sections in real-scale shown the foamed bitumen mixes have performed very well in highways with high to medium traffic level. Structural evaluation over the first two years showed an increasing trend on the stiffness of the section influenced basically by the curing process. Foamed bitumen stabilization shown better performance in terms of surface distress that sections treated with Portland cement.

LIFE CYCLE ASSESSMENT OF WASTE PREVENTION ACTIVITIES: METHODOLOGICAL APPROACH AND CASE STUDIES FOCUSED ON PACKAGING

Simone Nessi - Supervisor: **Mario Grosso**

Waste prevention has become one of the pillars of the European waste management policy in the last decade. To help Europe to become a society that seeks to avoid waste and use them as resources, the member states are now required to develop national waste prevention programmes, setting quantitative objectives and appropriate measures for their achievement (Waste Framework Directive 2008/98/EC). The programmes should focus on the key environmental impacts associated with the whole life cycle of the products and the materials becoming waste, and pursue the dissociation of these impacts from the economic growth. In Italy, each Region is also required to prepare a regional waste prevention programme, defining further objectives and tangible actions to be implemented locally.
Both the European and the Italian waste legislation require that waste management and prevention options are chosen so that an overall positive environmental outcome is achieved, when the impacts associated with the whole life cycle of products are assessed. Thus, selected waste prevention measures and actions shall not only allow for a reduction in the quantity or hazardousness of waste, but also in the overall environmental impacts.

A comprehensive review of viable actions for the prevention of municipal waste was carried out as a first research step. It showed that most prevention actions are based on four main mechanisms, which generate different environmental consequences. Such mechanisms include: (a) the reduction in the consumption of products or services; (b) the substitution of products or services with less waste-generating equivalent ones; (c) the reuse of disposable or durable goods; and (d) the extension of the lifespan of durable goods. While a reduction in product or service consumption is expected to generate only environmental and energy benefits (provided that possible 'rebound effects' due to the increased income available to the consumers are not taking place), the other types of mechanisms also involve additional impacts (due, e.g., to the consumption of alternative products or services). The balance between avoided and additional impacts needs thus to be carefully evaluated, in a life cycle perspective, to properly assess the environmental and energy convenience of those waste prevention activities that are not based on the simple reduction in product or service consumption.
To support this claim, two life cycle assessment (LCA) case studies were then carried out, to evaluate the environmental and energy convenience of two municipal waste prevention activities based on product substitution. The first activity substitutes bottled water by public network water withdrawn from the tap or public fountains, to reduce the amount of waste generated from the consumption of drinking water. The second activity is instead based on the substitution of liquid detergents packaged in single-use plastic containers, by those distributed "loose" through self-dispensing systems and refillable containers, to achieve a less waste-generating distribution system. In both the assessments, different baseline scenarios using the substituted product (e.g. bottled water) were compared with two waste prevention scenarios using the alternative product (e.g. tap water). Each baseline scenario accounted for the use of a particular type and/or size of packaging for the substituted product, while the waste prevention scenarios depicted different ways of providing the citizens with the alternative, less waste-generating product. The results of the two assessments revealed that the ultimate environmental and energy convenience of a waste prevention activity based on product substitution can depend on different variables. Frequently, these variable depict the way the activity is actually implemented by the involved actors (citizens, institutions, producers etc.), but can also relate to the substituted product. Examples of these variables for the two examined prevention activities are the distance travelled by car to reach public fountains, the overall volume of water withdrawn at the fountains, the conditions in which the container used to withdraw tap water at the households is automatically dishwashed, the distance along which the replaced bottled water is transported to retailers or local distributors and the number of uses of refillable containers for loose detergents. The need of adopting a life cycle thinking approach to properly assess the environmental and energy convenience of waste prevention activities based on product substitution was thus demonstrated.
As a further research step, two alternative methodological LCA approaches (conceptual models) to incorporate waste prevention activities into LCAs of integrated municipal waste management systems were identified, presented and discussed. The definition of the approaches was based on both a structured reorganisation of the amendments already available in the literature into a common approach, and on further elaborations and research. The identified approaches were conceived for the comparison of waste management scenarios implementing specific waste prevention activities, with one or more baseline scenarios without waste prevention. They were characterised in terms of perspective on waste prevention activities, functional unit, system boundaries and of the resulting procedure for the calculation of the potential impacts. Both the approaches provide the same result in terms of difference between the impacts of a waste prevention scenario and a baseline one. As this difference represents the net impacts of the considered waste prevention activities and of any possible change in the management of the remaining waste, both the approaches can indifferently be used to evaluate the effects of implementing specific waste prevention activities in a real or fictional waste management system. Nevertheless, due to the partially different upstream system boundaries adopted by the two approaches, the results of single scenarios are different when calculated with one approach rather than the other. The interpretation of scenario's results needs thus to be carried out differently. For the same reason, the application of the two approaches will be more suitable in studies with different specific purposes. By defining a proper functional unit and setting adequate system boundaries, it is thus possible to apply LCA to municipal waste management systems which include all the options of the waste hierarchy and not only those that can be applied after the waste is generated.
Finally, to demonstrate the applicability of the identified methodology, the two waste prevention activities examined initially were implemented in a real waste management system, to evaluate the effects on its overall environmental and energy performance. The municipal waste management system of the Lombardia Region, Italy, was specifically selected for the assessment, as this region is based on an advanced management scheme and has set specific waste reduction targets for 2020. A 2020 reference scenario was thus compared with different waste prevention scenarios, where the two examined activities are both separately and contemporarily implemented, by assuming a complete substitution of the traditional product(s). The results showed that, when the overall life cycle impacts of the alternative product are lower than those of the substituted traditional product, the overall environmental performances of the waste management system are improved, due mainly to the additional upstream benefits of waste prevention (avoided production and use of the substituted product). The observed percentage improvements are generally higher compared to the percentage of waste prevented, but are not always appreciable. In fact, while for the bottled water substitution such improvements range mostly between 5% and 158%, for the liquid detergent substitution they exceed 3% for just one impact category.

OUTDOOR AND INDOOR NAVIGATION BASED ON PHOTOGRAMMETRY WITH LOW-COST SYSTEMS

Diana Pagliari - Supervisor: **Livio Pinto**

Nowadays, the demand for devices and applications that need navigation solutions is continuously growing. For instance, consider the constant and increasingly request of 3D mapping services or the development of application based on user's location. In some case is sufficient to know approximately where the sensor is located (i.e. at room level), but in a large amount of cases a more accurate solution is required.
The navigation problem has been solved for a long time using GNSS (Global Navigation Satellite System). However, the satellite systems can be useless in obstructed areas, such as downtown or inside buildings.
An interesting low cost option is represented by photogrammetry, assisted by additional information in order to scale the photogrammetric problem and obtain a solution also when the situation is critical for imaging based methods (i.e. poor texture on the frame scene).
In this PhD thesis the problem of recovering a navigation solution in critical areas has been faced developing low-cost systems for both indoor and outdoor areas.
In urban areas a positioning system based on photogrammetry, using urban map as constrain, has been developed and tested. The vehicle has been equipped with one or more digital cameras (pointing rightward to the building façades) and a GPS antenna (see Fig.1).
From the images acquired during the survey, a number of tie points is extracted using automatic algorithms; then these data are used as input to solve the bundle block adjustment problem, together with some Ground Control Points extracted from urban maps. Furthermore, in case some good quality satellite positions are acquired (i.e. in areas where the sky is more open, as in correspondence of squares or intersections) they are integrated within the photogrammetric solution.
The proposed method has been studied in the frame of UMALS project (High-speed 3D Underground utilities Mapping and Automatic electrical cable Lying System), whose final objective is to georeference a GPR (Ground Penetrating Radar) antenna in urban areas. Because this instrument has a very slow motion, a low-cost solution based on IMU (Inertial Measurement Unit) is not feasible. The investigated solution has been tested under different scenarios, recovering trajectory with a precision of 0.20 meters, or even better. The obtained results show how the accuracies of the photogrammetric solution significantly improves by adding some GPS pseudo-observation to the problem itself. In fact, these points are known with few centimeter of error, so they can be very useful to better constrain the solution and to correct some systematic error that can be present in urban maps too. Better results, in the order of few centimeter of error in all directions, have been obtained introducing also the relative orientation constrain between the two cameras installed on the vehicle roof. A series of simulations and preliminary tests have been performed. Finally, some kinematic tests have been realized acquiring a block composed by 600 images along a close trajectory, but also considering a block of 10 parallels strips, for a total of 301 images, allowing testing the proposed approach in different conditions. The second test represents a challenging situation from a strictly photogrammetric point of view because of the peculiar conformation of the block and the presence of a single flat building façade: the method has been proven reliable also under these circumstances. Furthermore, matching methods based on the trifocal test and multi-images approached have been widely tested.
Photogrammetry can represent a useful tool in order to define the followed trajectory indoor too. It can be useful not only for navigation purposes, but also for reconstruct the building itself. This last task is currently of topic interest for BIM (Building Information Model) creation. A method based on the integrated use of the data delivered by Kinect for Xbox One has been developed. This sensor could represent a very useful tool for small budget project because it allows combining together visual and depth data, which can compensate reciprocally their weaknesses. The Kinect sensor can be remotely controlled by a laptop and it is able to acquire RGB, infrared and depth images almost simultaneously, with a frame rate up to 15 fps. All the device image sensors have been calibrated, in order to define the error committed by this game controller when it is used as a measuring system. Finally, a kinematic test has been realized in an office building, installing the sensor on a cart (see Fig.2).

1. A schematic representation of a typical survey situation with the vehicle, equipped with two digital cameras and a GPS antenna, ready for the survey

2. The cart equipped with the Kinect, a laptop and a reflective prism used to track the reference trajectory

The collected data are combined together in order to reconstruct the trajectory followed by the sensor: the RGB images are used to identify tie points that are re-projected on the point clouds, generated from the depth maps. These points are used to estimate the rotation matrix between subsequent point clouds and, consequently, to estimate the followed trajectory. The trajectory has been recovered with an accuracy of 0.05 meters.

ANALYSIS OF BIOLOGICAL PROCESSES IN WWTPS FOR MANAGEMENT, CONTROL AND AUTOMATION

Dalila Pulcini - Tutor and Supervisor: **Prof. Roberto Canziani**
Co-Supervisor: **Ing. Luca Luccarini**

Introduction

Wastewater treatment plants are complex systems, where a large amount of information should be known to prevent failures and keep the plant running regularly. Some variables and parameters in wastewater treatment plants (WWTPs) may be conveniently monitored to gather information that helps in monitoring and controlling the bioprocess that occur in the plant. Up to recent years, automation has been considered costly in WWTP design, and it has been often neglected in the initial design of these plants. However, an adequate use of ICA (Instruments, Control and Automation) can make a plant run consistently and economically.
Although process control in SBR plants has been widely studied and implemented based on simple and roust indirect signals such as pH, ORP and DO, the same does not apply for CAS (Conventional Activated Sludge) plants.
The aim of this research is to study the indirect signals (pH and ORP) and biological process performance in continuous-flow activated-sludge plants in order to verify how these signals can be used to monitor and control the biological processes.

Materials and Methods

The experimentation was carried out in a thermostated (20°C) pilot plant at ENEA (Bologna, Italy), made of a reactor zone (pre-denitrification and oxidation tank), a pumping system (load, internal and external recycle), an aeration system and a secondary settler. The pre denitrification tank was continuously mixed but not aerated, while the nitrification one was kept aerobic (DO = 1.5-2.5 mg/l) through an on-off controller actuating an air pump. The sludge settled in a sedimentation tank and was recycled to the anoxic tank. The pilot plant was fed with a synthetic wastewater simulating a real municipal wastewater. The pH of the influent has been monitored during all the experimentation and was maintained at 7.5.

Results and Discussion

Three different operating condition of denitrification process have been recognized, through the continuous monitoring of pH and ORP signals in anoxic tank. In particular, we found that ORP value identify the operational state of the process in a pre-denitrification system, anoxic, oxic and anaerobic, while pH trend detect when a transition among these states is happening. Results have been classified according to three cases, two of them defined anomalous and the third one normal.
Case 1 (anomalous): ORP >> 0mV (around 100mV); NO_x^- > 0 mg/l; meaning "too low carbon/ Nitrogen ratio".
Case2 (anomalous): ORP << 0mV (=~ -350 mV); NO_x^- = ~ 0 mg/l; meaning: "Too high C/N ratio".
Case 3 (normal): ORP~ 0 mV (operative range =~-250mV ; -50mV), NO_x^- = ~ 0 mg/l; Correct C/N ratio.
Operation strategy should be able to detect Case 1 and 1 and to bring automatically the system back to Case 3, which is the only admissible operative case that can ensure the correct operating processes in a waste water treatment plant.

Case 1

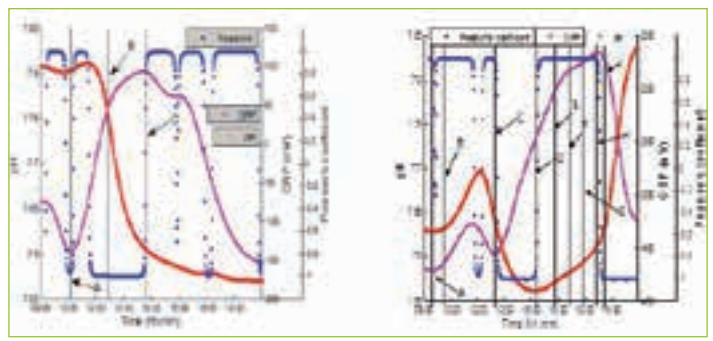
The aim of this strategy was to decrease the recirculated nitrate in order improve the denitrification process operating in condition different from the normal condition. After few hours ORP decreased to below -150mV, and oxidized nitrogen compounds reduced to near zero. In the same time, pH increased rapidly, passing from 7.6 to 7.8. It is noticeable that the first "pH knee" occurs when ORP starts decreasing. This fact means that only after nitrates reduced to near zero, ORP passed from a highly positive value to a highly negative value. On the other hand, the decrease in pH revealed the start of nitrification activity. The maximum pH value occurs when ORP becomes constant at around -150mV (i.e.: denitrification is completed).
Evaluating the correlation coefficient it's noteworthy that the signals pH and ORP are always correlated, but during the transition from Case 1 to Case 3 the correlation is always negative.

Case 2

When ORP was around -350 mV in the anoxic tank, this indicated that denitrification process was complete, but a considerable residual soluble COD (> 20 mg/l) was still present. The internal recycle flow was gradually increased to increase the nitrate load to the denitrification tank. Finally, when the internal recycle was increased until the ORP profile started to increase. Again the correlation inverted its sign and was effective in actuating the corrective action.
All the information described are reported in the following figure (Fig.1): in red the ORP signal, in purple the pH signal and dots blue are Pearson's coefficient values.

Conclusions

The relationship between pH/ ORP profiles and biological processes taking place in each phase of an SBR cycle is well-known. On the contrary, this relationship has not been sufficiently investigated, yet, in continuous flow reactors. This study indicates that there is the possibility to achieve important information about the denitrification process by monitoring pH and ORP in the anoxic tank. In particular ORP characterizes typical operational conditions (e.g.: excess carbon and lack of nitrate, or vice versa, or, finally, a balanced ratio of the two), while pH trend indicates possible transitions between two different conditions (e.g. due to variable influent COD/N ratios) and the Perarson's coefficient shall be used to monitoring the transition.
These results persuade that continuous measurement of pH and ORP allow an effective monitoring of the denitrification process in CAS plants, as a consequence of the availability of biodegradable organic carbon for denitrification, which is expressed as the COD/N ratio in the influent wastewater.



1. Signals profiles for anoxic tank, in RED the ORP, in purple pH signal and dots blue are Pearson's coefficient. On the left is represented the Case 1 and on the right the Case 2.

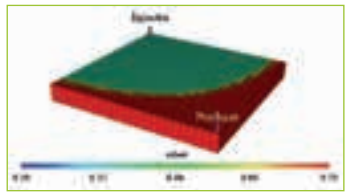
CHARACTERIZATION OF MULTIPHASE FLOW IN POROUS MEDIA UNDER WAG INJECTION SCENARIOS

Ehsan Ranaee - Supervisor: **Prof. Alberto Guadagnini**
Co-Supervisors: **Prof. Monica Riva** and **Dr. Giovanni Porta**

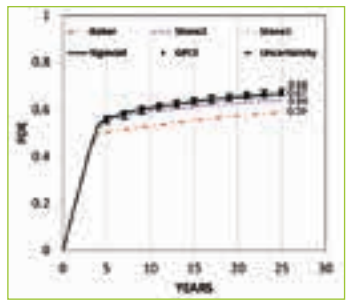
With the ongoing advancements in enhanced oil recovery (EOR), 5 to 15 percent increase of oil recovery is reported after implementation of Water Alternating Gas (WAG) injection in reservoirs which have been previously exploited for several years under primary and/or secondary recovery techniques. It is expected that a fraction of residual oil remobilizes due to trapping of gas phase in the regions previously exploited through waterflooding. This process can improve oil recovery by combining increased mobility (macroscopic sweep efficiency) and enhanced pore-scale displacement (microscopic sweep efficiency) of the oil phase.
Prediction of key features of reservoir scale processes under WAG injection scenarios is typically performed through numerical simulation tools relying on a straightforward extension of Darcy's law to multiphase flow dynamics. Besides common uncertainties in characteristics of fluids properties (e.g., density and viscosity) and heterogeneity of the host rock matrix (e.g., porosity and permeability), numerical simulation of flow under WAG conditions requires coping with the intricate details of flow dynamics of three-phase systems. In this context, oil relative permeability plays a crucial role and need to be carefully characterized. Tasks undertaken during this research are associated with development, implementation and testing a new approach for the estimation of oil relative permeability, k_{ro}, under three-phase environments.
It is well known that oil relative permeability is generally affected by characteristics of rock properties, fluid properties and the interaction between rock-fluid and fluid-fluid properties. Only a few complete sets of laboratory experiments of three-phase flow are available to date. Empirical models are typically implemented to estimate oil relative permeability to be employed in field scale computations. These models are generally grounded on an interpolation of experimental relative permeability data observed under two-phase core-flooding experiences which then leads to estimates of relative permeabilities under three-phase flow conditions. Results collected in this work show that the ability of typically used interpolation models to interpret experimental data is quite limited. The most severe limitation of simple interpolation models is their inability to capture hysteresis effects, i.e., the dependence of oil relative permeability on saturation path history.

The aim of this research is to (see Figure 1): (*i*) analyze the set of existing relationship between three-phase oil relative permeability and key input variables typically considered, (*ii*) characterize a novel methodology for the prediction of three-phase oil relative permeability, and (*iii*) introduce a workflow for the implementation of such model in black oil reservoir simulators. A first set of results relies on the statistical study of a set of core-flooding experiments available from the literature. We characterize the relationship that links oil relative permeability to the commonly considered state variables (e.g., phase saturations and saturation ending points). Our results show that commonly employed linear interpolation strategies are not appropriate to reproduce observed three-phase oil relative permeability, even as prior information about saturation ending points is available from three-phase measurements. Results also demonstrate that three-phase oil relative permeability exhibits a clear correlation with oil saturation, initial and residual oil saturation and two-phase oil relative permeabilities observed in an oil-gas system. A mild negative correlation is also found between oil relative permeability and trapped gas saturation.
A key result is the development of a nonlinear sigmoid-based model to incorporate information of initial and ending point conditions from two-phase (e.g., water-oil and oil-gas) oil saturation-relative permeability datasets. This modeling strategy enables one to (*a*) obtain estimates of three-phase k_{ro}, and (*b*) capture key effects of the pore-scale phase distributions which occur in a three-phase environment and are not included in currently available models. The robustness of the proposed methodology is assessed and demonstrated through comparison of model parameters estimates obtained by relying solely on two-phase data against their counterparts estimated within a Maximum Likelihood (ML) framework on the basis of three-phase measurements. Results obtained through this working hypothesis are compared against two sets of experimental data. The comparisons reveal that most experimental observations are accurately reproduced by the proposed model, which can also include wettability effects. Finally, the model is implemented in the *ECLIPSE* black oil simulator to assess the field scale performance of this model in comparison with commonly used three-phase relative permeability/hysteresis models. To this end, we consider a simple synthetic homogeneous reservoir (Figure 2) and compare the performance of our model against that of other existing models in predicting field oil efficiency (FOE) and residual oil saturation, S_{or}. We also perform a preliminary global sensitivity analysis (GSA) of the system behavior, in view of future applications of the model to reservoir characterization (Figure 3).
It is expected that future applications of this semi-empirical model may comprise diverse field-scale conditions associated with WAG injection protocols, including the analysis of, e.g., history matching and well placement, control and optimization strategies.

1 Workflow of the research.



2 Synthetic reservoir developed for the assessment of the Sigmoid-based relative permeability model in field scale applications.



3 Time evolution of field oil efficiency (FOE) as rendered by the Sigmoid-based model in comparison with other commonly employed relative permeability models. Symbols (•) and (–) respectively represent the mean and width of uncertainty bounds for *FOE*.

INTEGRATION OF OPTICAL AND RADAR SATELLITE DATA FOR NATURAL RESOURCES MONITORING

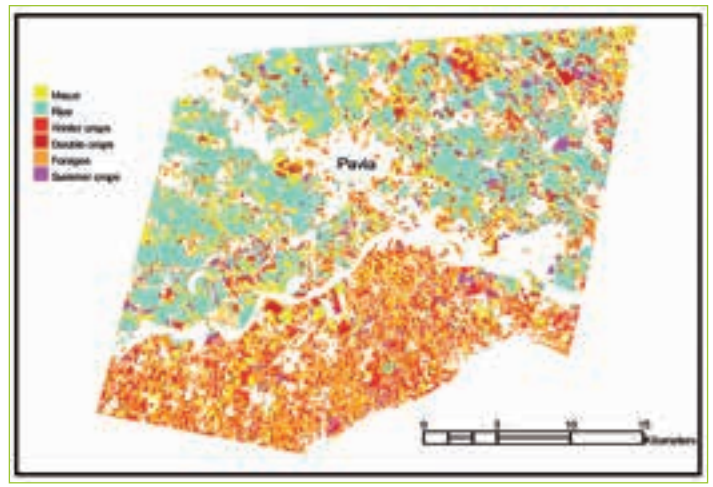
Ramin Saidiazar - Supervisor: **Pietro Alessandro Brivio**

Since the first satellite missions in the early '70s, remote sensing has been playing an increasingly important role as a source of data/information for environmental studies. With the launch of more sophisticated satellites, the amount of data and its availability to the scientific community has increased. Two classes of Earth Observation (EO) satellite sensors are nowadays available: passive and active sensors. The former, depends on the Sun's reflected and/or emitted spectral radiation from the target, the latter is able to send a signal and to measure the received radiation backscattered from the Earth surface.
Focusing on land vegetation monitoring, passive satellite sensors operate in optical/ thermal wavelengths domain. By measuring the radiation reflected from the vegetated canopies, in the visible and near-infrared domain, satellite sensors provide information on the photosynthetic activity of vegetation and leaf internal structure; at the longer infrared (thermal) wavelengths they measure the amount of energy emitted from the surface and reaching the sensor as an indicator of the thermal conditions of the vegetated surfaces (i.e. water stress). The radiation emitted from SAR (Synthetic Aperture Radar) sensors and backscattered by the surface, is instead sensitive to the geometry, texture and dielectric properties of the vegetated surfaces. Moreover, SAR sensors operating at longer wavelengths, are least affected by cloud cover and atmospheric conditions. Optical and microwave sensors are therefore complementary for operational vegetation monitoring, although these two branches of remote sensing have operated for a long time independently; it is now recognized that several fields of application would benefit from their integration.
The thesis' research has focused on the feasibility of synergistic exploitation of optical and radar satellite data for natural resource monitoring and, specifically, for monitoring natural vegetation disturbances (i.e. mapping the areas affected by fires) and agriculture (i.e. mapping crop extension and types).

In case of burned area mapping, the study area was chosen to be Portugal due to historical records of fire happened in this area and burning of nearly 45% of the country's surface in 30 years. Landsat-5 Thematic Mapper (TM) data provided by NASA and ENVISAT Advanced Synthetic Aperture Radar (ASAR) data provided by ESA were used. After analyzing different types of data from ENVISAT ASAR, the single look complex (SLC) data were used to calculate backscattering signal from the burned surfaces. A fuzzy burned area mapping algorithm, an approach that relies on multi-criteria of convergence of partial evidence of burning provided by different spectral indices (SI) in order to derive the layers of candidate seeds and candidate region growing boundaries, has been refined to integrate the information brought by both optical SIs and SAR imageries (pre- and post-fire temporal difference of the backscattering coefficient). The difference image between pre- and post-fire acquisitions highlights burned areas as characterized by a backscatter greater than the surrounding unburned vegetation. This property was used in the region growing module of the fuzzy algorithm to reduce the likelihood of selecting false seeds. Burned area maps obtained (Figure 1) show that SAR data can bring substantial amount of information to enhance mapping accuracy: by decreasing commission errors, the overall accuracy increases. In the second application, the integration of SAR and optical data has the objective to classify different types of crops at the regional scale and to simulate near-real time mapping of crop types with

1. Burned area mapping and its accuracy using optical and SAR data over Portugal for the year 2003.

specific interest in the reliability of a map delivered early during the crop season. The study area is located in Northern Italy, where independent information were available for validation by Regione Lombardia. Landsat-8 Operational Land Imager (OLI) and ASI (Agenzia Spaziale Italiana) Cosmo SkyMed images, optical and SAR data respectively, were collected to build a multi-temporal dataset. The Enhanced Vegetation Index, Red Green Ratio Index and the Normalized Difference Flood Index were used for optical data and sigma naught value of the backscattering for the SAR data. Three different classification algorithms have been tested: Maximum Likelihood, Minimum Distance and Spectral Angle Mapper. Classification of crop types was carried out at two levels of detail: one with 15 classes and one with 7 classes. Moreover, classification accuracy has been evaluated at different time steps in order to simulate near-real time mapping during the crop season. Maximum Likelihood provided the best results with an overall accuracy for early crop mapping (at the end of July) of 87.7%. These results are satisfactory for the use of the crop map in a monitoring system that provides information for public and private decision-makers (Figure 2).
General conclusion upon the research carried out on both topics is that the integration of SAR and optical data improved accuracies in both applications. SAR can play a unique role in maintaining mapping accuracy at a satisfactory level by replacing and/or complementing the optical information and could fill the gaps where there are limitations to optical data such as cloud cover or nighttime imaging. The main idea is that for natural resources monitoring we should be able to exploit multi-sensors data by developing new advanced and more appropriate techniques for fully exploitation of the information content of Earth Observation satellite data. The analysis of techniques for optical and SAR data integration takes an important role in the perspective of future satellite missions such as the ESA-Sentinels, which will provide consistent and continuous data for natural resource monitoring.



2. Crop map from integration of optical and SAR data using Maximum Likelihood classification with 7 classes of detail.

THE DEFORMATION PATTERN OF ECUADORIAN ANDES REGION FROM PERMANENT GNSS NETWORK

Serrano Richard - Supervisor: **Sansò Fernando**

The Global Navigation Satellite System (GNSS) data is being extensively used for various purposes all around the world. This Doctoral thesis presents the development of deformation pattern of Ecuadorian Andes based on GNSS permanent network. In the last years, Geocentric Reference System for the Americas (SIRGAS) consisting of multiple GNNS networks has been set and operating in South America. In Ecuador, *Red de Monitoreo Continuo del Ecuador* (REGME) network consisting of multiple GNNS permanent stations has been operating since 2009.
The aim of REGME is maintaining an Ecuadorian Geodetic Reference Framework updated and compatible with positioning techniques available today and a reliable collection of geographic data that can be applied in cadaster, reference for relevant government projects and monitoring earthquakes and tectonics activities.
In this research, we investigate 13459 days of positioning data of 9 REGME stations located in continental Ecuador. GNSS observations recorded were evaluated and the time series analyses were conducted to determine the station behavior. As result of the trend analyses of time series it was determined that the stations moves to north east direction (8.5 mm/year). This result agrees with the region´s tectonic plate movements.
The algorithm can be used to determine deformations in areas where the people are in risk of getting hurt and in areas with unstable landslides. It could be used to monitor the movements of buildings, earthquake zones, bridges, etc.
The development of a deformation monitoring network in Ecuador based on GNSS Rinex observations is presented. A stochastic mathematical analysis is applied to time series in order to determine the stations behavior. The algorithm is developed in Matlab. Results from thesis show that it is possible to detect deformations in the order of a few millimeters.
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HETEROGENEOUS PHOTOCATALYSIS AND ELECTROPHOTOCATALYSIS ON NANOSTRUCTURED TITANIUM DIOXIDE FOR WATER AND WASTEWATER TREATMENT: PROCESS ASSESSMENT, MODELLING AND OPTIMIZATION

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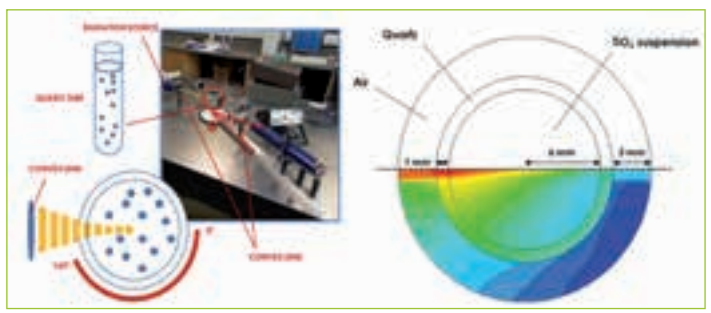
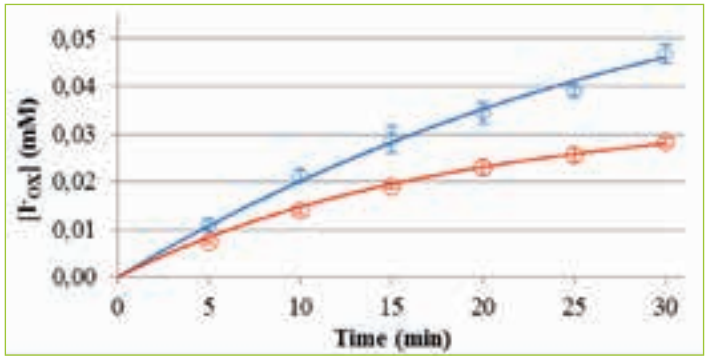
Titanium dioxide (TiO_2) photocatalysis is one of the most investigated innovative processes for water and wastewater treatment since TiO_2 photoelectrochemical properties make it an excellent material for promoting advanced oxidation. Current challenges in the development of affordable and sustainable technological applications at full-scale are mainly related to (i) the photocatalyst heterogeneous phase which enhance the complexity of the chemical-physical processes involved, and (ii) the low process yield with respect to other established advanced oxidation processes, such as ozone or hydrogen peroxide combined to UV radiation. Therefore, further research is required, addressed to a deeper understanding of the fundamental mechanistic phenomena involved in TiO_2 photocatalysis, and to the process optimization and scale-up. These topics are faced in the present PhD thesis, which is structured in four sections, as briefly described in the following.

- The first section is focused on modelling the optical behaviour of TiO_2 suspensions. In detail, an innovative methodology for the characterization of the optical properties is proposed: experimental measurements were performed by an optical goniometer (figure 1a), followed by a modelling phase, developed by means of a multi-purpose CFD code and reproducing the radiative fields in the experimental setup (figure 1b). The effectiveness of the proposed methodology was proved by integrating optics, fluid dynamics and chemical reactions in a CFD model, simulating the degradation of oxalic acid in a semi-batch annular photoreactor.
- In the second section the implementation of two experimental protocols for the measurement of reactive species is described, namely photogenerated holes and hydroxyl radicals, at the laboratory scale. These protocols were applied for assessing the reactivity of suspensions of commercial TiO_2 nanoparticles. A model for reactive species quenching has been developed, accounting for radiation transfer, TiO_2 nanoparticle aggregation and kinetic reactions, and it was calibrated by means of experimental data collected in an experimental setup (UV1). The model has been validated by measurements carried out in a different experimental setup (UV2), being the model capable of effectively predicting experimental data, as reported in figure 2.
- The third section concerns the assessment of the influence of several inorganic anions - namely carbonate, chloride, nitrate, phosphate and sulfate - on the photocatalytic reactivity of commercial TiO_2 nanoparticles in suspension and immobilized self-ordered nanotubular TiO_2. In detail, the production of reactive species, namely photogenerated holes and hydroxyl radicals, has been monitored over time in the presence of dissolved species in solution. In case of TiO_2 suspensions, the influence of inorganic anions on TiO_2 aggregation, evaluated by laser scattering techniques, is described too. As for self-ordered nanotubular TiO_2, this innovative engineered nanomaterial was grown by anodic oxidation and characterized. Moreover, special attention was dedicated to the evaluation of nanotubular TiO_2 fouling and to the definition of a regeneration protocol for the photocatalytic material. For both photocatalysts the detrimental effect of inorganic anions has been discussed and a modelling procedure for the influence of inorganic anions on photogenerated holes based on competitive adsorption has been proposed, highlighting the effectiveness of Langmuir-Hinshelwood mechanism and the importance of mass transport phenomena for nanotubular TiO_2. Model kinetic parameters were estimated at various operating conditions.
- In the fourth section an optimal design methodology for an electrophotocatalytic reactor using self-ordered nanotubular TiO_2 for water and wastewater treatment is discussed. Such procedure is based on the use of generated photocurrent as an indicator of TiO_2 photoactivation. In detail, generated photocurrent was monitored as a function of two operating conditions, namely reactor configuration and solution transmittance. Then, a modelling procedure for maximizing the generated photocurrent in an electrophotocatalytic reactor was developed, whose effectiveness was validated in several reactor configurations. An optimization surface is reported in figure 3.

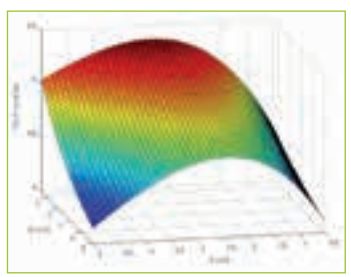
Finally, the appendix is dedicated to the CFD simulation of fluid dynamics and radiation transfer in an unbaffled stirred tank reactor for TiO_2 nanoparticle photocatalysis at the laboratory scale. The effectiveness of CFD code in describing fluid dynamics was proved and the mixing conditions were assessed. CFD model was calibrated by radiometric measures and radiation transfer was described, determining radiation intensity and local volumetric rate of photon adsorption in the reactor.



1. Radiative field modelling: (a) goniometer for optical properties estimation, (b) CFD simulation of the experimental setup.



2. Oxidized iodide concentration vs. time: experimental data obtained in UV1 (diamonds) and UV2 (circles) setup, simulated data obtained in UV1 (blue line) and UV2 setup (orange line).



3. Optimization surface, as generated photocurrent per supplied power (PC/P), vs. cylinder radius (R) and external irradiation distance (D) in triangular base unit configuration at 100% solution transmittance.