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Software utilized for image-based velocimetry methods focused on water resources

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ABSTRACT

Sustainable water resources management plans require advanced instrumentation to measure accurately both the water velocity and the discharge of the aquatic bodies. An innovative way to achieve this goal is with the use of non-contact, cost-effective, and efficient image-based methods. A studied water surface can be captured by subsequent images while surface velocity can be estimated by the movement of tracers on the water's surface. Various software have been developed in order to utilize such tracing algorithms and to monitor the surface velocity of fluids. The objective of this study was to present the current status of these software, describe the main parameters, and provide applied examples of image-based velocimetry application. To achieve this firstly, a comprehensive review was conducted that focused on the scientific publications that have utilized particle image and tracking velocimetry methods on water bodies. Secondly, the main scope of this research was to record and analyze these publications based on the software that were used. This paper presents 30 software with their main features and few of their application examples. This should help other researchers choose the appropriate image-based velocimetry software to measure water velocity and discharge based on the needs of their study.

Keywords: Fluid analysis; Hydrometry; Image velocimetry; Natural tracers; Seeding particles; Software database; Streamflow velocity; Tracking velocimetry; Water resources management

1. Introduction

Surface-water demands are rising due to the increase of the world's population and water consumption footprints. These facts require water managers to achieve a more accurate analysis of the flow measurements and consequently of the freshwater availability [1]. To accomplish this cost-effectively and efficiently, water managers need innovative flow instrumentation to measure those resources more accurately, in real time, and in more detail. New and emerging developments in flow instrumentation have significantly improved our capabilities to measure more quickly and accurately the surface-water velocity, discharge, and flow dynamics of streams and rivers [2].

The traditional methods primarily relied on mechanical velocity meters that have a propeller to measure its revolutions per second. During the last decades, new methods have been developed (acoustic and radar instruments) due to the technological evolution and the availability of inexpensive computers and electronics [3]. The evolution of digital cameras and unmanned aerial vehicles (UAVs), as well as their decrease in cost have led to the application of image-based (or video) analysis techniques on water resources both in laboratory and natural environments

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settings [4]. The image-based analysis techniques have been used for more than three decades, starting from 1984, to measure the water velocity vectors primarily in laboratories [5]. Still these methods are used primarily by scientists and researchers although they have a great potential to provide a cost-effective method for water managers and practitioners. The use of a non-contact velocity measurement system is the major advantage of image-based techniques because it ensures human's safety, especially during peak discharge and flood events [6]. An image-based system can be divided in the following categories: (a) investigated fluid, (b) particles/tracers, (c) hardware (e.g., digital cameras, light source, strobe or laser, and synchronizer), and (d) software [7].

Image-based techniques use two different approaches: (i) the Eulerian approach, where the velocity is a function of position and time, and (ii) the Lagrangian approach, where the tracing approach of each floating particle on the surface of water is utilized. Examples of the above approaches are the particle image velocimetry (PIV) and particle tracking velocimetry (PTV), respectively [8]. The algorithms frequently used in PIV analysis are based either on the spatial domain via cross-correlation (CC) or on the frequency domain via fast Fourier transformation (FFT). There are many variations of the PIV method for laboratory condition such as stereoscopic PIV, multi-plane stereo PIV, holographic PIV, tomographic-PIV, and micro-PIV [9]. On the other hand, in the Lagrangian approach, PTV can detect and track individual particle tracers by various correlation algorithms such as integrated cross-correlation and relaxation, four time-steps model, pattern matching model, spring model, heuristics, and Voronoï tracking scheme to identify target particles movement in space [10].

In the mid-1990's, Japanese researchers used the PIV method in large scale riverine environments and the name large scale particle image velocimetry (LSPIV) was adopted [1]. Major advancements have been realized by researchers from the USA in the last 10 y by implementing this method in both natural and laboratory water flowing conditions [11]. The LSPIV is emerging as a new and innovative technique that is changing the way to measure surface water resources. However, the method still requires further development in order to become globally adapted, especially by water managers and practitioners. Currently, it has been tested by using images from UAVs, helium balloons or by placing them on a fixed location over the water body (bridge, tree, fixed vehicle, etc.) [3]. The main difference between LSPIV and the traditional PIV is the scale, as the name states LSPIV is for a "large scale". LSPIV has been applied mainly in the natural environment, in contrast to PIV that is applied primarily in laboratory conditions. The images can be captured parallel to the water surface but in most cases, the camera is at an oblique angle in regard to the measurement surface [12]. For this reason, the captured LSPIV images need to be ortho-rectified before image interrogation by using a few selected ground control points (GCPs), that can be either natural (trees, rocks, etc.) or man-made objects (buildings, pillars, targets, etc.) that are included in the images [13].

As it was already mentioned, the floating particles and/or the free-surface deformations are a necessary consideration for the image-based methods. The flow tracers can differ based on their size and reflectance in contrast to laboratory conditions (e.g., no natural light from the sun) [1]. These tracers can be natural floating objects and free-surface patterns (e.g., light floating debris, foam, wood, leaves, ice blocks, etc.) [14]. When natural tracers are insufficient, artificial seeding is needed to visualize the flows. It is desirable that the seeding particles should be environmentally friendly, harmless, and biodegradable material (e.g., leaves, mulch, grass, pop-corn, cornstarch, etc.) [15]. In addition, there are many different seeding approaches (e.g., from bridges or cranes, confetti machines and cannons, multipoint seeding points, transecting the flow, etc.) [1]. When the texture of the free water surface is less visible and there are no sufficient tracing particles, the surface waves of the stream flow can be used to measure the velocity by applying the space-time image velocimetry (STIV). STIV identifies the brightness variation in a searching line set parallel to the main flow direction compared to the continuous images [16]. This method is more suitable, when the stream flow is not complex, while it can provide a high calculation speed and computation efficiency [17]. Even with proper illumination, it is difficult to determine the movement of the tracer particles without suitable cameras. Typically, high speed digital cameras are used for PIV analysis, either equipped with complementary metal-oxide semiconductor (CMOS) or charge-coupled device (CCD) image sensors [18,19]. Furthermore, red–green–blue cameras (RGB), near-infrared (IR), and thermal image IR cameras are frequently used for LSPIV [20]. In addition, UAVs coupled with high-definition cameras are rapidly and widely applied in a huge variety [21]. The setting of the frame rate is important in order to avoid possible errors that may arise in cases of under/over sampling [22]. The frame rate of the camera must be at least 15 frames per second (fps), while typical recording session durations are about 2 min with a minimum of 60 s that corresponds to 100–400 image pairs [23,24].

Review articles that present the image-based methods already exist such as for PIV [12], PTV [8], LSPIV [11], STIV [16], or the popular tracers that are used [15]. The innovation of this study is the presentation of the software that are most frequently used on image-based velocimetry methods as well as the parameters used in different applied examples. In addition, the analyzed data were represented graphically as a framework to be used by other researchers. The information provided by the current research will enhance in the further development, adjustment, acceptance, and adoption of these optical methods by more Governmental organizations, universities, research institutes, public authorities, and generally stakeholders that are associated with water resources management issues. The objective of this study was to provide the current status of image-based velocimetry software and highlight basic parameters used in selected examples from the literature review. The ultimate goal was to provide a framework that can help identify and utilize the most suitable tool for image-based velocimetry application. The application of this relatively easy and cheap methodology by expert scientists or trained personnel would significant help in the more cost-effective implementation of Water Framework Directive 2000/60/EU and Floods Directive 2007/60/EU that the EU foresees and imposes on its members for the monitoring of the quantity and quality of their water resources.

2. Materials and methods

2.1. Data source

This study reviewed scientific publications that focused on specific image-based methods that calculate the velocity and discharge of natural water bodies. The software utilized on these water bodies were recorded and presented. Examples of different software applications were selected in order to present parameters that were frequently used for their selection, for example, camera specification or method mostly used by each software. This study was not a comparison on the performance among the different software as it was not possible to test all of them on a real study area. In addition, the software that was frequently utilized in laboratory conditions either at large or smaller scale application on water resources were included. The review concentrated on publications published online from 1997 till 2019 (including 2019). The keywords "water", "PIV river", "PTV river", "LSPIV", "STIV", and "LSPTV" were used in several search engines such as Scopus, Science Direct, Research Gate, Web of Science, Microsoft Academic Research, and Google Scholar which are the most well-known and well-used.

2.2. Data collection

The search in these engines resulted in more than 1,200 articles, but only the 512 that were relevant to the subject matter of the review were utilized (Supplemental file-research data). These relevant articles were published in journals, proceedings of symposiums, congresses, conferences, workshops, but also included technical reports, books or book chapters, theses, and dissertations. There are probably more publications especially in other languages (e.g., proceedings, thesis, and books) that were not captured by this review. In addition, publications such as hardcopies were not included in this article because they are not readily available and difficult to access. The publications were downloaded and stored as "pdf" files in a common folder.

2.3. Data processing

A database (dB) was created based on the stored publications. Firstly, we reviewed all publications and excluded those which were not relevant or duplicated and we found the most frequent software used in these studies (with at least one-two references). At the second stage, we created different categories/columns based on the parameters that were characteristic for each software. The next step was to record each entry of these parameters in the dB. Furthermore a diagram was created as a framework for water managers in order to select the best software based on the scope of the study and the requirements of their application.

3. Results and discussion

The general chronologic distribution of the reviewed publications from 1997 to 2019 is shown in Fig. 1. There is an increasing trend concerning the annual number of publication. Specifically the number increased from 4 in 1997 to 41 in 2019. The most productive years with more than 30 publications were: 2018 (52 publications), 2014 (47 publications), 2015 and 2011 (each 44 publications), 2019 and 2016 (each 41 publications), and 2017 (33 publications) and 2013 (31 publications). These results show the increasing trend of publications because of the evolution in the technology, resources, and instrumentation. In addition, the average number of co-authors per publication increased from 2 in 1997 to 4 in 2019. Based on the above observations, there is an increasing interest in these methods and their application on water resources. Furthermore, more scientists, but also groups of scientists and even teams from different research institutes are collaborating and producing more applications and results based on these image-based methods.

In regard to the area of implementation, the reviewed publications were divided in two major categories: (a) laboratory studies and (b) field studies (Fig. 2). The publications reporting results conducted in laboratory conditions were 199 while the publications reporting field studies were 305 publications. There were studies that applied the methods in both laboratory conditions and field studies. The laboratory conditions were further divided into: (a1) open lab channels (80 publications), (a2) flumes (71 publications), and (a3) models that represented natural environments (48 publications). The field studies were separate into: (b1) rivers (201 publications), (b2) streams (46 publications), (b3) artificial irrigation channels (16 publications), (b4) under bridges (12 publications), (b5) urban flooded areas (7 publications), (b6) alluvial fans (4 publications), (b7) dykes (3 publications), (b8) fish ladders (3 publications), and (b9) drainage perimeters (2 publications). Finally, there were field studies that had just one publication such as (b10) lakes, (b11) ponds, (b12) tsunami, (b13) airport, (b14) marine, (b15) estuaries, (b16) coastal, (b17) embankments, (b18) sewer systems, (b19) dam gates, and (b20) stormwater detention basin.

Overall several publications were in laboratory conditions because of the technologically advanced facilities in the well-known research institutes that host large open channels and flumes. These facilities can lead to valid results under controlled conditions that have helped the advancement and improvements of these methods. Still, more publications were conducted in field conditions, especially rivers and streams. This is also necessary in order to validate and calibrate the image-based methods in real-life conditions that require more variables that impact the water bodies (e.g., wind, sun reflection, etc.). In addition, it appears that the focus is on rivers and streams since it is more difficult and more time consuming to measure stream flow in the field because they are highly variable temporally and spatially, they are renewable and they are the main water freshwater resource for most countries. Concerning the field studies there was a great variety of where they had been applied (20 sub-categories). This indicates that the methods have applicability in many different environments and the greater acceptance of these methods by different scientists.

There are various software that analyze images and calculate the surface velocity. Most of them were developed for either PIV or PTV analysis. The most frequent software were recorded and are presented in Tables 1–3. The Tables 1–3 showcase selected publications that were analyzed in order to provide the main highlights of each software. Table 1 includes the programming language, the method mostly used, the algorithms for analysis, the availability,

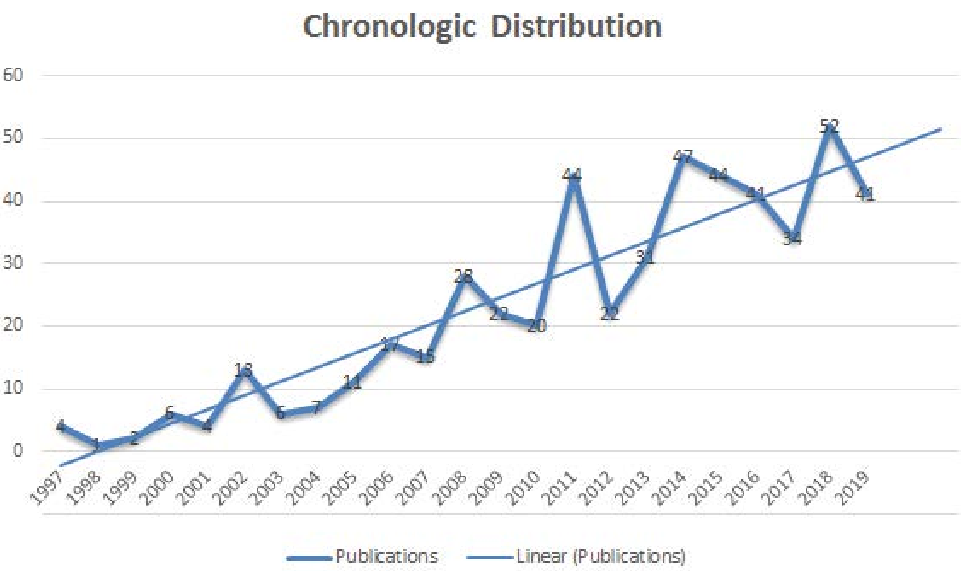

Fig. 1. Chronologic distribution of all reviewed publications related to image-based velocimetry methods covering the period 1997–2019.

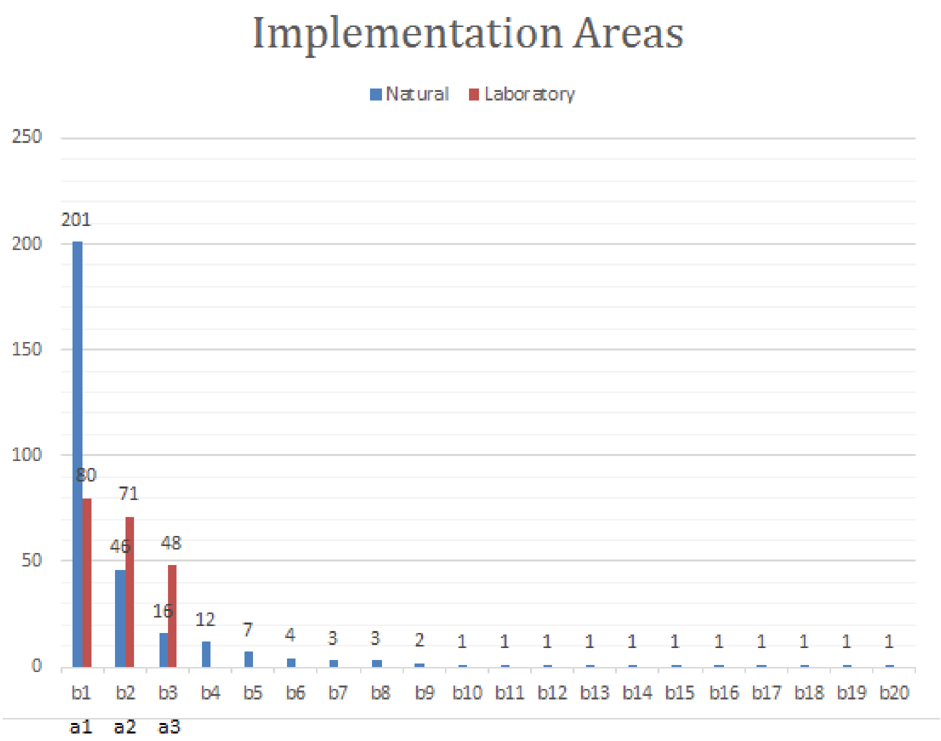

Fig. 2. Implementation areas of the reviewed articles. Initially divided into two major categories laboratory (a_n) and natural areas (b_n) and further subdivision.

and the website of each software. Table 2 is focused on the recorded examples (at least one example of an application) and provides the authors, the year, the location, and the study area. Table 3 contains the tracers used (seeding particles), the camera specifications, the video/images used, and if there is an ortho-rectification option. The description of the most frequent software recorded in this research was followed with a general comparison among the image-based methods through these software. This list is not exhausted but provides the most frequently used. Most studies do not provide information about the software used, the description in some is just the type of the software, for example, "LSPIV", and there are many studies that mention an in-house software or programmed algorithms in MATLAB.

Table 1
Software recorded in the literature review and the main highlights on the different parameters (programming language, the method mostly used, the algorithms for analysis, the availability, and the website of each software) used in each software

Software	Programmed in	Method mostly used	Algorithms for analysis	Website	Availability
Fudaa-LSPIV	FORTRAN and Java	PIV, LSPIV	CC	https://forge.irstea.fr/projects/fudaa-lspiv	Open-source
PIVlab	MATLAB	PIV, LSPIV	CC + FFT	http://pivlab.blogspot.gr	Open-source
PTVlab	MATLAB	PTV, LSPTV	CC – relaxation	http://ptvlab.blogspot.gr	Open-source
RIVeR	MATLAB	Post-processing	For ortho-rectification	http://riverdischarge.blogspot.com/	Open-source
Mat_LSPIV	MATLAB	LSPIV	CC	https://orbi.uliege.be/handle/2268/167695	NR
DIGIMAP	MATLAB	LSPIV	CC	NR	NR
KU-STIV	NR	STIV	RICOH, SIFT	http://www.kobe-u.ac.jp.html	Commercial
Davis	NR	PIV	CC	https://www.lavision.de/en/products/davis-software/	Commercial
Flow Manager	NR	PIV	FFT	http://flowmanager-software.software.informer.com	Commercial
FlowIQ	MATLAB	LSPIV	CC + FFT	NR	NR
EdPIV	NR	PIV	FFT	https://www.lcgui.net	Open-source
SmartPIV	NR	PTV	6 algorithms	https://www.softpedia.com/get/Science-CAD/Fluere.html	NR
VidPIV	Java	PIV, PTV	CC – FFT	https://www.oxfordlasers.com, https://www.ila.de	Commercial
MatPIV	MATLAB	PIV	CC – FFT	http://www.mn.uio.no/math/english/people/aca/jks/matpiv/	Open-source
JPIV	Java	PIV	Multi-pass, multi-grid, FFT	http://www.jpiv.vennemann-online.de	Open-source
mpiv	MATLAB	PIV	CC	http://www.oceanwave.jp/softwares/mpiv/	Open-source
URAPIV/PyPIV	MATLAB and PYTHON	PIV	CC	http://urapiv.wordpress.com/	Open-source
OpenPIV	MATLAB, Python, and C++	PIV	FFT	http://www.openpiv.net	Open-source
OpenPTV	C++ and Python	PTV	FFT	http://www.openptv.net	Open-source
OSIV	Pre-built binary package, and source code or MATLAB	PIV	CC – FFT	http://osiv.sourceforge.net	Open-source
GPIV	ANSI-C	PIV	FFT	http://gpiv.sourceforge.net	Open-source
LSPIV App	Android and IOS	LSPIV, STIV	NR	https://sites.google.com/site/rtsubaki/lspiv-app	Open-source
Discharge App	Android	LSPIV	NR	https://discharge.ch	Open-source
PIV APP	Android	PIV	NR	NR	NR
GeoPIV	MATLAB	PIV	CC – FFT	http://www.geopivrg.com	Open-source
Tracker	Java	LSPIV	NR	https://physlets.org/tracker/	Open-source
PIVDEF	NR	Stereo PIV	CC	NR	NR
PIVMat	MATLAB	Post-processing of PIV results, visualization, and statistics	Many algorithms	http://www.fast.u-psud.fr/pivmat/	Open-source
ADMflow	NR	PIV	Advection-diffusion equation	http://admflow.net/tiki-index.php	NA – Requires registration
AREDIS	MATLAB	LSPIV	CC	NR	NR

NA means not applicable; NR means not recorded.

Table 2
Software recorded in the literature review and the main highlights on the different parameters (the authors, the year, the location, and the study area) used in each software based on selected research articles

Software	Authors [Citation]	Year	Location	Study area
Fudaa-LSPIV	Le Coz et al. [27]	2014	Cauterets France, IOWA USA, Bratislava Slovakia	Uono River 160 m width
PIVlab	Tauro et al. [28]	2015	Lab in Italy, and Brooklyn, New York, USA	Lab Plexiglas shallow-water tank, 1.6 m × 1.6 m × 0.2 m
PTVlab	Tauro and Grimaldi [33]	2017	Trento, Italy	Lab flumes, (A) 8 m × 0.25 m and (B) 5 m × 3 m
RIVeR	Patalano et al. [10]	2015	Pisco Perú, Cordoba, and Sante Fe Argentina	(A) 0.3 m wide laboratory flume and (B) two low-order natural streams
Mat_LSPIV	Wardman et al. [40]	2011	California, USA	Natural brook
DIGIMAP	Muste et al. [41]	2009	Iowa, USA	Lab. rectangular perspex tank 1,400 mm × 1,400 mm × 300 mm
KU-STIV	Fujita et al. [43]	2019	Niigata, Japan	Uono River 160 m width
Davis	Weitbrecht et al. [45]	2011	Karlsruhe, Germany	Lab Plexiglas shallow-water tank, 1.6 m × 1.6 m × 0.2 m
Flow Manager	Kantoush et al. [47]	2009	Lausanne, Switzerland	Lab flumes, (A) 8 m × 0.25 m and (B) 5 m × 3 m
FlowIQ	Harpold et al. [50]	2006	Virginia, USA	(A) 0.3 m wide laboratory flume and (B) two low-order natural streams
EdPIV	Tauro et al. [52]	2013	Viterbo, Italy	Natural brook
SmartPIV	Shi and Chen [55]	2011	Liverpool, UK	Lab. rectangular perspex tank 1,400 mm × 1,400 mm × 300 mm
VidPIV	Meselhe et al. [56]	2004	Louisiana, USA	Lab rectangular flume
MatPIV	Kuok and Chiu [60]	2013	Kuching, Malaysia	Perimeter drain
JPIV	Meunier et al. [62]	2013	Windsor, Canada	5 L glass tank (51 cm long × 25.4 cm wide × 30 cm high, black aquarium gravel
mpiv	Rueben et al. [64]	2015	Oregon, USA	Rectangular box, 2.1 m height and area 48.8 m × 26.5 m
URAPIV/ PyPIV	Shavit et al. [66]	2007	Haifa, Israel and Channel Islands, California	Laboratory flumes, ocean (Santa Barbara Channel Islands)
OpenPIV	Sivas et al. [69]	2016	Istanbul, Turkey	Laboratory plexiglas channel flume, height = 4.15 m, width = 20 mm
OpenPTV	De la Torre et al. [72]	2019	Fornebu, Norway	small tank 1.50 m × 0.40 m × 0.40 m
OSIV	Suri et al. [73]	2014	Atlanta, Georgia, USA	Lab
GPIV	Higham et al. [75]	2017	Karlsruhe, Germany	18 m × 1.82 m shallow lab water flume
LSPIV App	Tsubaki et al. [76]	2015	Japan	Grayscale fractal pattern
Discharge App	Luthi et al. [78]	2014	Zurich, Switzerland	Open channel
PIV APP	Chang et al. [80]	2016	Taiwan	(1) Newspaper (2) Straight flume with honeycomb filter
GeoPIV	Kaczmarek and Leśniewska [83]	2010	Poland	Flood embankment model
Tracker	Brauneck et al. [84]	2019	Bretzenheim, Germany	River Nahe brunch sections width: 8.20 m depths: (A) 0.70 m and (B) 0.30 m
PIVDEF	Mohajeri et al. [88]	2016	Trento, Italy	Laboratory tilting flume (width 0.4 m; depth 0.4 m; length 6 m gravel bed
PIVMat	Naves et al. [90]	2019	La Coruna, Spain	Laboratory physical model of street scale urban drainage
ADMflow	Novak et al. [92]	2017	Ljubljana, Slovenia	Laboratory (A) glass flume with dark glass bottom, 0.5 m × 6 m × 5 m and (B) concrete 1 m × 20 m × 0.6 m
AREDIS	Bechle et al. [93]	2012	Taipei, Taiwan	River-estuary system (Danshui River)

NA means not applicable; NR means not recorded.

3.1. Fudaa-LSPIV

The Fudaa-LSPIV was developed in FORTRAN by the electricité de France (EDF) and Irstea (French Environmental Research Institute) and was further advanced in Java by DeltaCAD. This software is available in both English and French [25]. It is a very frequently used software for LSPIV analysis because it is user-friendly and uses statistical cross-correlation algorithms to track the movement of tracers in portable gray map (PGM) format gray-scale images [26]. It also performs a geometrical transformation that relates the camera viewpoint with real-world coordinates based on the GCPs measured in the field. The transformation parameters are 11 unknowns that can be calculated by solving the equation based on at least 6 known GCPs. The software was utilized in both laboratory and field conditions by Le Coz et al. [27].

3.2. PIVlab

The PIVlab was developed in MATLAB by the University of Groningen in The Netherlands. It has a user-friendly graphical user interface (GUI) and is a powerful tool to calculate velocities in fluids in the laboratory [28]. For this reason, it does not provide ortho-rectification; only the known reference distance between two points is provided [29]. Despite this shortcoming, it has been used for field conditions, especially when the camera is almost parallel to the water body (e.g., UAV) [30]. The PIVlab offers two approaches of window deformation for the motion analysis of the images: (i) a single pass direct cross-correlation (CC) that finds and matches the particle pattern from the interrogation area A back in the interrogation area B and (ii) a direct Fourier transform correlation with multiple passes and deforming windows (FFT) [31]. Tauro et al. [28] used PIVlab on images captured by UAV field experiments over a natural stream.

3.3. PTVlab

The PTVlab was developed by the National University of Córdoba in Argentina and University of Sheffield in United Kingdom based on the codes of the PIVlab [32]. The PTVlab detects the particles by: (i) binary correlation, (ii) Gaussian mask, and (iii) dynamic threshold binarization techniques [33]. The particle tracking can be executed either with cross-correlation or the iterative relaxation labeling technique, or a hybrid of the two approaches. In addition, it can extract from a video the continuous images/frames in the required format for the analysis [34]. Tauro et al. [35] modified and simplified the algorithm used in the PTVlab for the PTV-Stream approach that does not require the need of results from the interpolation. Tauro and Grimaldi [33] combined the software with thermal cameras to capture the movement of ice dices on the surface of natural streams.

3.4. Rectification of image velocity results

The rectification of image velocity results (RIVeR) software was developed by the Center of Study and Water Technology (CETA) and the National University of Córdoba in Argentina [36]. It is a very useful tool that ortho-rectifies the results from PIVlab and PTVlab when transforms the projection of the image on real-world coordinates by using at least four GCPs [37]. The latest version of this software also calculates the discharge based on bathymetry measurements. In addition, this software can extract the frames from a video in order to process them properly. Patalano et al. [10] used the software to ortho-rectify the results of PIVlab and PTVlab in various experiments.

3.5. Mat_LSPIV

The Mat_LSPIV was developed by The University of Iowa in MATLAB [38]. Cross-correlation is computed between an interrogation area in the first image and the interrogation areas located within a search area in the next image [3]. There are two options in order to calibrate and ortho-rectify the images, either manually by adding the GCPs (at least six GCPs) or uploading a predefined file while applying a transformation algorithm of eight projective transformation parameters [39]. The Mat_LSPIV can calculate the discharge based on bathymetry measurements. Wardman et al. [40] used Mat_LSPIV to study and monitor rural streams during high flows.

3.6. DIGIMAP

The DIGIMAP was also developed by The University of Iowa in MATLAB [38]. The software is a very similar tool to the Mat_LSPIV. It has the same capabilities, the same cross-correlation algorithm for the LSPIV analysis and the same implicit calibration equations. In addition, the DIGIMAP can calculate the water discharge based on bathymetry measurements while it can also plot geomorphological features on the riverbed and floodplain. The software was used in combination with a mobile LSPIV data collection system [41].

3.7. KU-STIV

The STIV is a LSPIV-inspired method developed by Kobe University that analyzes the variation of the brightness or color differences in a searching parallel line to the main flow direction as it is recorded [42]. The method can be applied by the KU-STIV software that combines various algorithms [43]. The displacement, rotation, and size change between the consecutive images are detected by using an algorithm known as RIPOC while the algorithm named SIFT, is used to detect the feature points in the respective image and record the track based on coordinates of detected feature points [16]. The software also provides a stabilization method for videos and ortho-rectification. The disadvantage of this software is that is not freely available online. Fujita et al. continue to improve the algorithms of the STIV methodology by using synthetic images captured obliquely from a riverbank but also with new indices to evaluate the quality of space-time images as recorded [43].

3.8. DaVis

The DaVis is a commercial software package from LaVision [44]. The DaVis supports a large number of

Table 3
Software recorded in the literature review and the main highlights on the different parameters (the tracers used (seeding particles), the camera specifications, the video/images used, and if there is an ortho-rectification option) used in each software based on selected research articles

Software	Tracers used	Camera/video used	Images used	Tool for ortho-rectification
Fudaa-LSPIV	Floating objects, turbulence patterns	Digital Camera (A) from riverbank under bridge and (B) above river and model	256 grayscale	Yes at least 8 GPRs
PIVlab	(A) 7 mm disc-shaped paper and (B) algae blooms	(A) UAV with GoPro cam. gimbal, Full HD, 60 Hz and (B) Canon VIXIA HF R300 30 fps, height = 4 m	8-bit grayscale	NA – only 2 points known distance
PTVlab	Regular and red-dyed ice dices (28 mm × 28 mm × 23 mm)	FLIR Systems AB ThermaCAM SC500, 7 m above river, monochrome videos, 5 Hz, 318 × 197 pixels (px)	8-bit grayscale	NA – only 2 points known distance
RIVeR	NA	UAV and Sony (WX300) 1,920 × 1,080 px. 30 fps	Extract 8-bit grayscale	For PIVlab and PTVlab 4 GPRs
Mat_LSPIV	Natural patterns (debris, bubbles, and turbulence)	Sony HDR-HC9 Digital Camera on a pan tilt device 1,440 × 1,080 px. 30 fps	500 frames 8-bit	Yes 8 GPRs
DIGIMAP	Wood mulch, grass, and leaves	Olympus C730 Digital Camera on tilted position 15–50 ft above 1,280 × 960 px	JPG 24-bits	Yes 6 GPRs
KU-STIV	Free-surface deformations	High-definition camera from the left bank	RGB BMP frames	Yes
Davis	Buoyant polyester glitter, 0.5–1.5 mm	CCD camera (Imager Compact, La Vision GmbH, 12-bit 1,024 × 1,024 px, 10 Hz, 256 cm above	Grayscale 12-bits	NA fixed position of up to eight cameras
Flow Manager	White and painted polypropylene particles	SMX-150 camera Dig. cam. 2,206 × 3,000 px. video 33 fps	Grayscale 12-bits	NA
FlowIQ	White wood beads and starch packing peanuts	Pelco monochrome CCD camera mounted on a metal tower, oblique, 640 × 480 px., 25 fps	8-bit grayscale 25 images at 25 Hz	Yes – 12 GCP
EdPIV	Ripples, fluorescent particles, and polypropylene particles	Miniature water proof Bullet HD 1,080 px	RGB frames and G index	NA
SmartPIV	50 µm diameter polyamide	ASTCAM ultima APX-RS camera fitted with a Nikkor 24–85 mm lens, 1,024 × 1,024 px, 125 fps	100 pairs, bit, 992 × 1,004 px.	NA
VidPIV	Black polypropylene particles	Digital camera 30 fps	8-bit BMP grayscale	NA
MatPIV	Orange ping pong balls	Digital SLR camera	JPG	NA
JPIV	White polyamide particles	Video camera 25 fps	PNG, TIFF, PGM, IMX, IM7	NA
mpiv	60-cm square white plywood	Argus Cameras 1,280 × 960 px. 8 bit, 5 and 2 Hz	8-bit grayscale	Argus Database

URAPIV/ PyPIV	GS hollow glass spheres, PG propylene glycol droplet (suspended sediment, phytoplankton, and zooplankton	CCD cameras	8 and 12-bit grayscale	NA
OpenPIV	Naturally buoyant particles	High speed camera	TIFF, JPG, BMP	NA
OpenPTV	White plastic sheets and diffuser sheets	(A) Photron FASTCAM SA5, 500 fps, 640 × 1,024 px and (B) 4AOS Promon U1000 Mono cameras 350 fps, 1,280 × 720 px	Tiff 8-bits	NA
OSIV	Sprinkling glass microspheres	Fire-I web camera AVI Video	Tiff 8-bits	NA
GPIV	2.5 mm hexagonal polyester particles	1.5 m above CCD-sensor camera 1,200 × 1,200, 37 Hz	12-bit resolution	NA
LSPIV App	Natural patterns	Smartphones, iPhone 5s, and iPhone 6plus	Video from smartphones 852 × 640 px and 1,440 × 1,080	Smartphone sensors
Discharge app	Natural patterns	Huawei Ascent Y300 android smartphone	Video from smartphone	Yes – 4 GCP
PIV APP	(1) Letters movement (2) NR	Smartphone 1,280 × 720 px.	Grayscale	Yes – 4 parallel laser beams
GeoPIV	Water level	NR	JPG	NA
Tracker	Table tennis and tennis balls, wooden chips of 5–8 cm	(a) DJI Phantom 3 Pro, (b) DJI Matrice 600 4k video at 30 fps	Video reduced to 5 fps	YES – at least two GCP to locate and scale
PIVDEF	Sieved pollen particles of 0.075 to 0.125 mm	High-speed Fastcam 500 Hz sampling frequency	NR	NR
PIVMat	3D-printer fluorescent particles (0.85 mm)	Lumix GH4 cameras, 25 Hz, 3,840 × 2,178 px, focal length 28 mm	1,500 frames (60 s)	NR
ADMflow	White polyethylene grains	Dig. Camera Casio EX-F1, 300 fps, 512 × 384 px.	50 images 512 × 384 px	NR
AREDIS	Lighted buoys	Flea2 cameras placed in bridge 500 m 1.2 MP CCD sensor 1,280 × 960 px. 30 frames/s.	NR	YES – at least 15 GCP

NA means not applicable, NR means not recorded.

hardware components (cameras, sensors, and optics) mostly used in Stereo-PIV or tomographic PIV system. The Stereo-PIV in DaVis are fully parallelized even for a single image as it uses an adaptive multi-pass cross-correlation PIV-algorithm [45]. The software provides very good pixel (px) accuracy per interrogation region and researchers state that the PIV algorithm is acceptable when an appropriate time delay is used between images to keep the particle image separations between 10% and 30% of the final interrogation window size [46]. LaVision provides many free add-ons to support the software such as Tecplot® 360 for 3D graphical presentation. Weitbrecht et al. [45] used the software in laboratory experiments to study environmental flows.

3.9. FlowManager

The FlowManager is a commercial software provided by Dantec Dynamics. It was developed for flow analysis that emphasizes on the stereoscopic PIV by using a FFT algorithm for a robust correlation but is also applied for LSPIV analysis on water resources [47]. In addition, the software includes a good calibration technique that uses a well-defined grid of dots, which are usually mounted on a traverse system [6]. Kantoush and Schleiss [47] performed LSPIV analysis by using FlowManager in eight different environmental flow and hydraulic engineering applications conducted in laboratory conditions.

3.10. FlowIQ

The FlowIQ is a PIV analysis software that was developed by Virginia Tech in collaboration with Aeroprobe Corporation based on DPIV [48]. This software includes DPIV algorithms, sizing algorithms, PTV, image pre-processing, and post-processing options for DPIV in a single windows-based platform [49]. The DPIV algorithm, which is one of the well-tested in laboratories, is based on a hybrid scheme that integrates a dynamically adaptive cross-correlation method with a PTV algorithm. Although, developed for the DPIV, there are studies that used it with LSPIV in both laboratory and low order streams [50].

3.11. EdPIV

The EdPIV was developed at the IIHR – Hydroscience and Engineering. The software contains FT-based cross-correlation algorithms for both PIV and PTV processing [51]. Each image is subdivided into 32 × 32 pixels interrogation windows and cross-correlation is performed using the standard FFT formulation with the Gaussian subpixel interpolation [52]. The image processing algorithm uses single-exposed multiple frames for a pattern matching approach that performs correlations on the gray-level values contained in small regions of the imaged area [53]. Tauro et al. [52] applied the software in a natural small stream and they used fluorescent particles as seeding material.

3.12. SmartPIV

The SmartPIV is an auto-procedure in order to propose the best particle tracking algorithm on the input images. The six algorithms available to select from are: (a) FFT cross-correlation, (b) discrete window offset cross-correlation, (c) iterative multigrid cross-correlation, (d) iterative image deformation cross-correlation, (e) Suerp-PIV, and (f) Kalman filter tracking [54]. Shi and Chen [55] analyzed all these algorithms and developed the software in order to be able to select the proper one based on specific parameters.

3.13. VidPIV

The VidPIV is another commercial software developed by Optical Flow Systems Ltd., for the PIV analysis, including the 3D PIV analysis, but it can also be applied to the LSPIV [56]. The user can choose the time interval, combinations of processing nodes (e.g., cross-correlation based on FFT, particle tracking), filtering, reprocessing (e.g., adaptive correlation), post-processing, and data extraction operations from the images [57]. Meselhe et al. [56] utilized VidPIV on low velocity shallow flume flows to investigate the LSPIV sensitivity to seeding density and time interval.

3.14. MatPIV

MatPIV is a free open source MATLAB toolbox developed by the University of Oslo in Norway. It also happens to be one of the oldest and most widely used softwares. It performs cross-correlation using FFT for the PIV analysis [58]. This code is able to track the movement of the particles effectively and produce the required vector plot using a loop ability. The user can modify it as the source code is available under the terms of GNU General Public License [59]. Coordinates can be defined, instead of using the camera coordinates (pixels), providing the advantage of real measurement units concerning the displacement (cm), and velocity outputs (cm/s). The surface flow velocities are calculated in a 2D matrix form as described in the Kuok and Chiu's [60] article where the MatPIV was applied on a drainage perimeter by using orange ping pong balls as seeding particles.

3.15. JPIV

The JPIV is a Java implementation developed mostly for micro PIV purposes [61]. The program is an open source, platform independent, and available under the terms of GNU General Public License [59]. The JPIV searches corresponding particle patterns in two sequenced images by using cross-correlation to visualize the surface velocity. Meunier et al. [62] used the JPIV to visualize and characterize flow fields generated by fish.

3.16. mpiv

The mpiv is a PIV toolbox written in MATLAB code and developed mainly for educational purposes for undergraduate and graduate student [63]. It consists of two programs; one for image processing and the second for data post-processing. It is portable, easy to use, and easily modifiable because the developer's intention was to keep the codes short, simple, and robust [59]. The software can be used for debris movement and tsunami inundation over an unobstructed beach in a laboratory wave basin [64].

3.17. URAPIV/PyPIV

The URAPIV uses a non-normalized correlation function [65] that performs a single cross-correlation pass for the PIV analysis and it can be recognized in many versions [66]. There is an open source MATLAB toolbox for the PIV analysis. In addition, the PyPIV is a Python version of the URAPIV that calculates the displacement field in pixels from two image files and writes it to a comma separated value (*.csv) data file [61]. Furthermore, there is a version of a 32 bit Windows executable software that accepts many image formats. The output data is written into a five column, tab-delimited text (*.dat) file but generally the software is very slow and unable to perform in synchronous computers [59]. Shavit et al. [66] used the URAPIV to study the intensity capping and improve the cross-correlation in the PIV analysis.

3.18. OpenPIV

The OpenPIV is a group of programs and the successor of the popular URAPIV software [67] but this software is faster, more user-friendly, and much more flexible. It is provided in various versions: (i) MATLAB in a GUI environment, (ii) Python, C++ with Qt-based GUI, and (iii) graphics processing unit (GPU) accelerated version. It is used worldwide mainly for PIV purposes but it can be used in riverine and nearshore environments even in UAV utilization [68]. In addition, there is another software named spatial and temporal analysis toolbox which is a complementary software written in MATLAB to visualize the streamlines act as a post-processing tool for the OpenPIV and other software [69].

3.19. OpenPTV

The OpenPTV is a 3D-PTV software based on the core algorithms developed in the C++ version at ETH Zurich while Tel Aviv University released the Python version PyPTV [70]. A spatio-temporal matching algorithm is used in order to perform the kinematic motion modeling with a time-dependent second-order polynomial and track the movement of particles. The relative position of the cameras needs to be defined [71]. De la Torre et al. [72] utilized the OpenPTV to study 3D PTV flow in bubble plumes from a free-falling jet. The software is mostly used for the PTV applications in laboratory conditions.

3.20. OSIV

The OSIV is programmed in C for Linux under a GNU General Public License and performs cross-correlation analysis of the PIV images [61]. The OSIV is an open-source software, so that users may contribute and modify it. In addition, it is available in many versions: (i) as binary package, (ii) as source code, (iii) as MATLAB toolbox, (iv), Windows, (v) Mac, or (vi) Linux platforms [73]. Suri et al. [73] performed the PIV analysis by using OSIV software in laboratory conditions.

3.21. GPIV

The GPIV is another PIV package programmed in C for Linux under a GNU General Public License and a binary format for the Mac OS X system [61]. The program includes the parameter settings, execution of routines for image processing, interrogation, data validation, post-processing, and finally a display of the results. The software uses multi-pass and image deformation techniques to calculate the velocity field [74]. Higham et al. [75] used the software to study the turbulence forms in a wake of a barrier during shallow flow conditions.

3.22. LSPIV app

A smartphone application that was developed to be used for both Android and IOS devices has been developed. This is the LSPIV app that was developed by Nogoya University in Japan for both the PIV and STIV analysis. It also provides ortho-rectification via the smartphone sensors without the need of the GCP measurements [76].

3.23. Discharge app

Another beta smartphone application is the discharge app developed by the Photrack AG Company (Zürich Switzerland) [77]. It can calculate velocity based on a recorded video, ortho-rectify it by placing marks, and also calculate the discharge based on water level measurements [78]. This application also stores the coordinates of the studied area in a worldwide database. The software uses the surface structure image velocimetry (SSIV) that introduces the following improvements compared to conventional LSPIV performance: (i) removal of glare and shadows on the water surface, and (ii) lack of traceable features in the flow [79]. Lüthi et al. [78] employed this mobile device application in open-channel conditions.

3.24. PIV APP

A team from the National Applied Research Laboratories and National Taiwan University, has developed a portable device for smartphones that includes lasers for ortho-rectification. The PIV APP application software was developed in the Android system for smartphones [80]. Actually, the specific app could not be found in Google Play Store, because it is probably still in the beta period and had not been launched by June 30th 2020.

3.25. GeoPIV

The GeoPIV is a free image analysis software developed in MATLAB at the University of Cambridge in United Kingdom [81]. The software was designed for the PIV analysis, by matching a cross-correlation using FFT, for geotechnical and structural engineering research applications [82]. The GeoPIV software is used to construct the displacement field in image-space coordinates, so the transformation to real coordinates must be further processed. The GeoPIV has been compared positively to other commercial PIV software although the processing speed is significantly slower [81]. Kaczmarek and Leśniewska [83] performed the PIV analysis through GeoPIV on a laboratory plane physical model of a flood embankment.

3.26. Tracker

The Tracker is a free software under a GNU General Public License is a free tool for video analysis based on the Open-Source Physics (OSP) Java Framework. The user has to define the image-patterns of the frames. The software compares these image-patterns between the frames and the outputs provide the displacement vectors of the surface velocities [84]. The tracker can run directly from its website or the BQ database on both Windows and Mac computers that have current versions of Java and QuickTime installed [85]. Brauneck et al. [84] selected this software to measure surface flow velocity of a natural river by using the UAV-based images.

3.27. PIVDEF

The PIVDEF software, is provided by the Italian Institute National for Studies and Experiences of Naval Architecture (INSEAN) [86]. The PIVDEF performs the analysis of a pair of images using overlapping, window deformation, and spurious vector filtering algorithms [87]. The software is used mostly for the stereoscopic PIV while it performs an iterative cross-correlation method. Mohajeri et al. [88] examined the turbulent flow field over gravel particles in order to understand the sediment transport in a gravel bed river by using the software in laboratory conditions.

3.28. PIVMat

The PIVMat Toolbox for MATLAB contains a set of command-line functions to import, post-process, and analyze 2- and 3-components vector fields from the PIV and stereoscopic PIV among other applications. It has standard vector field operations such as interpolation, filtering, averaging, derivatives computation (vorticity, divergence, strain, etc.) while it provides many advanced statistics [89]. It is compatible with several data formats, including DaVis, DynamicStudio, VidPIV, and MatPIV. In addition, it has been used in a LSPIV application as a post-processing software for velocity vectors produced by the PIVlab. Naves et al. [90] used the software in laboratory conditions on street-scale urban drainage physical model to study runoff using fluorescent seeding particles.

3.29. ADMflow

The ADMflow is a free software package for velocity field calculation from a time series of flow images. It has already seen flow measurement applications in many areas of hydraulic research [91]. The software enables the quantification of velocities of the flow pollutant and is based on the advection-diffusion law. The uncertainty is estimated to be in the range of 5% according to Novak and his team who studied shallow rectangular waste-water channels [92].

3.30. AREDIS

The AREDIS stands for automated river-estuary discharge imaging system. It incorporates: (i) a dual-camera system that captures the river with optimum image resolution and coverage area, (ii) a field-based rotational camera calibration technique, (iii) bridge pier generated wake patterns to track velocity with LSPIV, and (iv) cost-effective lighted buoys as or night tracing particles [93]. The LSPIV method is utilized by using a GUI program developed in MATLAB. The AREDIS GUI includes a main menu interface to access the rest of the subcomponents: (i) calibration, (ii) ortho-photo generation, and (iii) velocity/discharge measurement [94]. Beckle et al. [93] tested the system in three river type measurements: (i) under normal flow, (ii) under typhoon event, and (iii) during night.

3.31. Other

The list presented in this review is not exhausted in regard to software for PIV analysis in laboratories. Other software possibly exist but either are not mentioned by name (e.g., MATLAB-based code) or are not further described or no information was found anywhere, such as FlowExpert 2D2C a commercial PIV software by KATOKOKEN Co., Ltd., (Kanagawa, Japan) [95], PTVResearch [96], LSIV50 and LSPIV2 [97], OpenFOAM and Flow-3D [98], DynamicStudio [99], Fluere [61], etc.

There are many free software that can be found on websites along with manuals, examples, and images. Some of them need a commercial license while others are not available online and for these reasons their application and overall information about them is limited. Most of the freeware is programmed in MATLAB or can be found in various version including Python, C, etc. In contrast, there are tools that can be used directly, for example, as Java application or even as a smartphone application which are very promising tools since everyone today, carries a smartphone. Some of them provide more options or are more user-friendly. The most of the oldest software are not supported anymore by developers or are not executable in the new versions of MATLAB. The variety of images is mostly found in the grayscale format after a simple processing. Most of these tools have been developed for the PIV or PTV analysis in the laboratory with very good performance even when utilized on larger scale laboratory models. There are software that have been developed directly the LSPIV, LSPTV, STIV methodology, or tools that were initially developed for laboratory conditions but they have been adapted in the field by many researchers. This gave the stimulus of

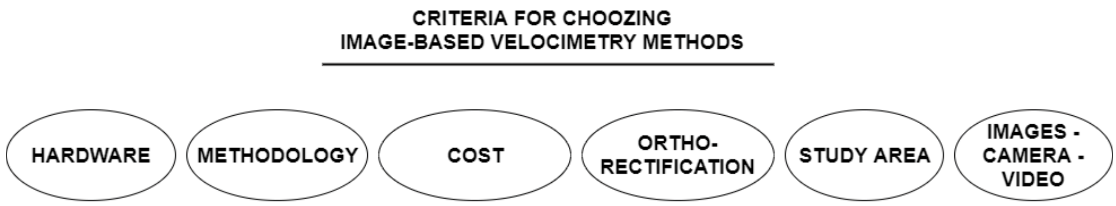

Fig. 3. Criteria for choosing image-based velocimetry methods.

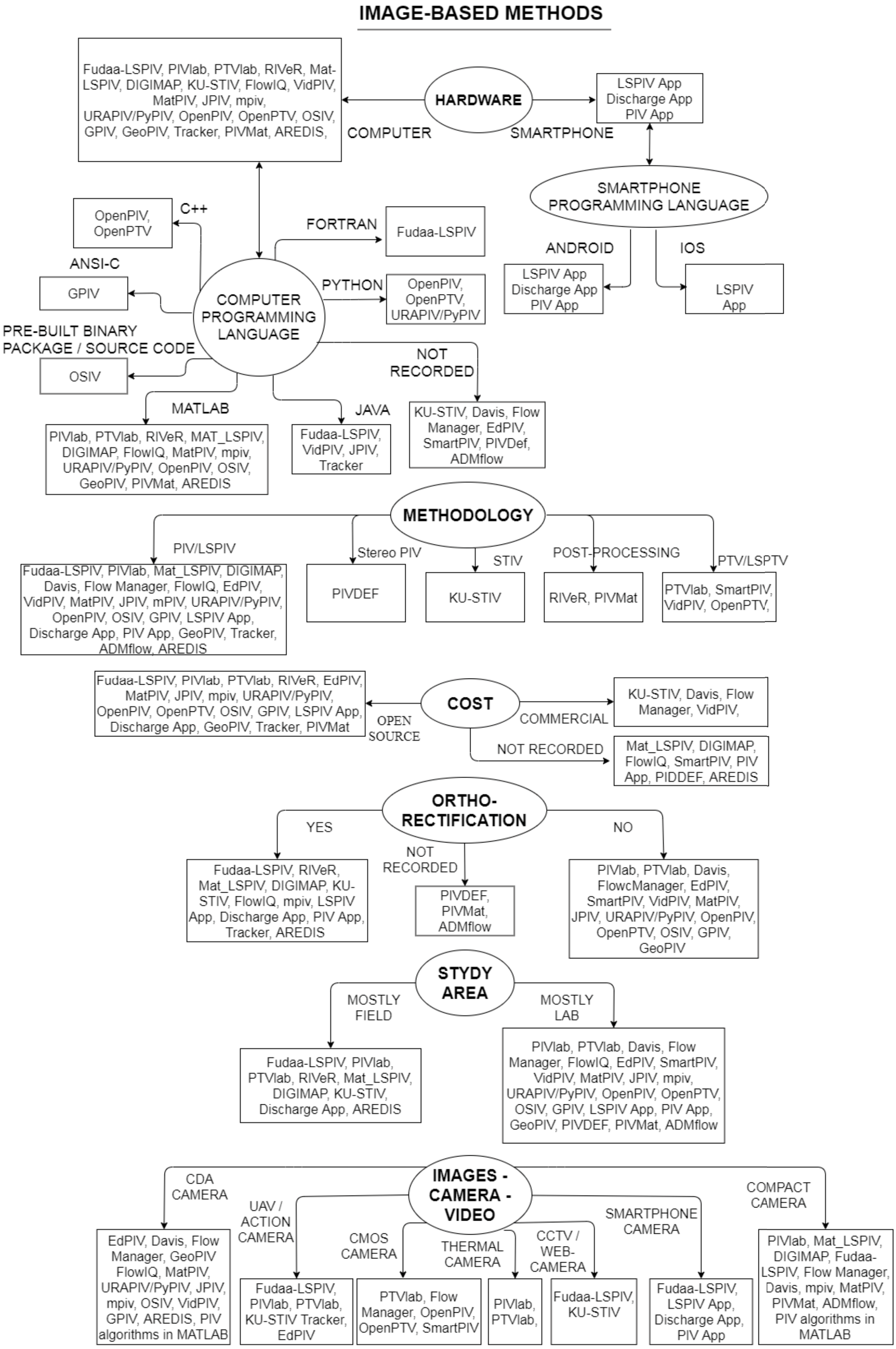

Fig. 4. Framework-diagram for choosing the best image-based velocimetry methods based on the six main parameters.

their broad application on natural streams and rivers flow conditions despite the variety of dissuasive natural factors affecting the methodology e.g. light, seeding particles, and weather conditions. There are tools that can be coupled with other software in order to ortho-rectify the images or calibrate known distance while some of them include the ortho-rectification step. All of them need seeding particles, artificial or natural, to analyze the motion of the water, and many different types of tracers have been recorded. This is one of the common points including the use of a low-cost hardware in contrast to other measurement tools. In contrast, various camera with different image/video resolution have been used including high-speed CMOS or CCD digital cameras and conventional digital cameras types: compact, modular, mirrorless interchangeable-lens, SLR-type digital single-lens reflex cameras to reduce costs. In the last decades, closed-circuit television (CCTV) cameras, internet protocol (IP) web-cameras, UAVs, and action cameras have become a frequent recording tool. The minimum color video resolution used was 100 × 100 px with a typical 1,920 × 1,080 px, while the maximum was 4,288 × 2,848 px. Additionally, the frame rate ranged from 5 to 500 fps with a typical value of 30 fps. This study was the first innovative attempt to record and list the most frequent software for image-based methodology. The most frequently used software were the PIVlab, Fudaa-LSPIV, KU-STIV, FlowManager, Davis, Mat_LSPIV, and EdPIV possibly due to the fact that the review focused mainly on natural water bodies and because many researchers did not named the software utilized in their application. Despite this, the software presented in this article had a wide range of application examples and overall image-based methods that were well-supported by the described tools. Although similar in concept, these software have different ways of modeling surface velocimetry, and consequently some are better suited for certain applications than others. There was a need to develop a framework that will include the software selection methodology depending on the nature of the application. The above-recorded information was utilized to create a diagram (flowchart) that can act as a framework for image-based velocimetry software on water resources. The framework (Fig. 3) was based on six crucial criteria: (i) hardware (type), (ii) methodology (type), (iii) cost (market value), (iv) ortho-rectification (requirement), (v) study area, and (vi) images/camera/video. Researchers can choose by going through each criterion (Fig. 4) which software they could utilize based on the software characteristics in coordination with the parameters needed for their studies.

4. Conclusions

This research was an attempt to present image-based methods, which are powerful tools as their development continues with applications in many different scientific fields, with an emphasis on water management. These methods are efficient and inexpensive compared to other current existing flow velocity instruments, while in addition as non-contact methods they provide greater safety to the recorder. This article covers research that has been conducted within the last 23 y and focuses on the software utilized in image-based methods used for water resources, especially natural water bodies but also includes laboratory applications that are relevant. The study showcases 30 software that were recorded and further analyzed by providing examples of applied research. The examples included different parameters such as programming language, the method mostly used, authors and year of publication, the location of the application, the study area, the tracers used (seeding particles), the camera specifications as well as the video and images used, if there is an ortho-rectification option, the availability, and finally the website of each software. A framework as a flowchart was produced based on six main parameters that help the water managers and modelers to select and utilize the most appropriate software based on their research needs. Finally for future work, we could incorporate these parameters as an online decision support system that could further assist experts in evaluating and selecting the most appropriate image-based software tool.

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