

Received: 19 Dec, 2017; Accept 23 Feb, 2018; Publish: 19 April, 2018

Preparation of Translated, Scaled, and Rotated ATS Drugs 3D Molecular Structure for the Validation of 3D Moment Invariants-based Molecular Descriptors

Satrya Fajri Pratama¹, Azah Kamilah Muda^{1✉}, Yun-Huoy Choo¹, Ramon Carbó-Dorca², Ajith Abraham^{1,3}

¹ Computational Intelligence and Technologies (CIT) Research Group,
Center of Advanced Computing and Technologies,
Faculty of Information and Communication Technology,
Universiti Teknikal Malaysia Melaka
Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
satrya@student.utm.edu.my, {azah, huoy}@utm.edu.my

² Institut de Química Computacional i Catàlisi, Universitat de Girona
17071 Girona, Catalonia, Spain
ramoncarbodorca@gmail.com

³ Machine Intelligence Research Labs (MIR Labs)
Scientific Network for Innovation and Research Excellence, Auburn, WA, USA
ajith.abraham@ieee.org

Abstract: The campaign against drug abuse is fought by all countries, most notably on ATS drugs. The technical limitations of the current test kits to detect new brand of ATS drugs present a challenge to law enforcement authorities and forensic laboratories. Meanwhile, new molecular microscopy imaging devices which enabled the characterization of the physical 3D molecular structure have been recently introduced, and it can be used to remedy the limitations of existing drug test kits. Thus, a new type of 3D molecular structure representation, or molecular descriptors, technique should be developed to cater the 3D molecular structure acquired physically using these emerging molecular imaging devices. One of the applications of image processing methods to represent a 3D image is 3D moment invariants. However, since there are currently no repository or database available which provide the drugs imaging results obtained using these molecular imaging devices, this paper proposes to construct the simulated 3D drugs molecular structure to be used by these 3D moment invariants-based molecular descriptors techniques. These 3D molecular structures are also translated, scaled, and rotated to measure the invariance properties of the 3D moment invariants-based molecular descriptors. The drugs molecular structures are obtained from pihkal.info for the ATS drugs, while non-ATS drugs are obtained randomly from ChemSpider database.

Keywords: ATS drugs, drugs identification and analysis, molecular structure representation, dataset preparation, preprocessing.

I. Introduction

Every country in this world is constantly interjected by the looming destruction potential of ATS drugs abuse, thus, United Nations feel obliged to combat these threats by establishing United Nations Office on Drugs and Crime

(UNODC) in 1997. Seized drug analysis plays an important part in the forensic investigation of drug-related crimes. The presence or absence of controlled substance in the seized materials heavily affects the outcome of criminal justice system [1]. Law enforcement entities and their respective forensic laboratories generally employ a set of acceptable standard techniques outlined by UNODC to detect the presence of ATS in the samples of seized drug materials [2].

One of the main reasons the ATS drugs abuse, including manufacturing and distribution, is very difficult to combat, is that it is mostly synthetic in origin [2]. Therefore, provided with sufficient technical knowledge, a chemist can derive a novel and unregulated structure of ATS and manufacture it in the clandestine laboratories, using various simple and flexible approaches [3]. The precursors to manufacture these drugs are also publicly available and can be purchased over-the-counter or as prescription medicine, albeit being the controlled substances [4]–[6].

These innovative designs proven to be a challenge for law enforcement entities and introduce a new layer of difficulties in detecting and identifying using existing laboratory techniques, which sometimes lead to both false positive and negative results, and thus, incorrectly outline the outcome of criminal justice court [7]–[10]. Thus, there is a continuous demand for the improvement of current laboratory techniques to recognize common characteristics of the ATS drugs. Due to these limitations, it is preferable to perform the identification by relying on computational intelligence methods [11], and taking advantage of the shape of molecular structures.

Despite the apparent need of reliable methods to detect and identify ATS drugs in the field of forensic toxicology, the use

of cheminformatics is only starting to be incorporated recently [12]–[18]. Cheminformatics researchers use molecular similarity to seek structurally similar compounds, since the drug design efforts are based on a principle which states that structurally similar compounds are more likely to exhibit comparable properties [19]–[23]. The success of molecular similarity depends on the molecular structures representation employed, also known as the molecular descriptors, which is discussed comprehensively in [24], [25]. There are various categories of molecular descriptors, although the most commonly used molecular descriptors are 2D and 3D molecular descriptors.

Since a molecular structure representation involves the knowledge of the relative positions of the atoms in 3D space, 3D descriptors usually provide more information and discrimination power for similar molecular structures and molecule conformations than 2D descriptors [26]. Searching for relationships between molecular structures and complex properties can often be performed efficiently by using 3D descriptors, exploiting their large information content [27]–[29]. This paper believes that molecular similarity can also be used to detect the similarity between unknown compound and reference compounds, and consequently, can be used to detect new brand of ATS drugs to the known samples of ATS drugs based on their molecular structure [12], [13], [16].

Recent advances in scientific domains have enabled the characterization of the physical molecular structure through molecular microscopy, such as by using transmission electron microscopy (TEM), scanning tunneling microscopy (STM), and more recently, non-contact atomic force microscope (nc-AFM) [30]. New discovery of tuning-fork-based nc-AFM provides a novel method capable of non-destructive sub-nanometer spatial resolution [31]–[35]. Single-molecule images obtained with this technique are reminiscent of wire-frame chemical structures and even allow differences in chemical bond-order to be identified [33]. The high-resolution images obtained using STM and nc-AFM reveals that the 3D model which is used for decades to depict molecular structure is virtually identical to the physical molecules, as shown in Figure 1.

Invariance with respect to labelling, numbering of the molecule atoms, and molecule translation and rotation is a required property of a molecular descriptor. Furthermore, it also must have a clear algorithmically quantifiable definition, and the values must be in an appropriate numerical range for the molecule set where it is applicable to [36], [37]. Since a molecular descriptor is independent of the characteristics of the molecular representation, it is possible to consider the molecular shape as an image, and thus apply image processing to represent the shape of the molecular structure.

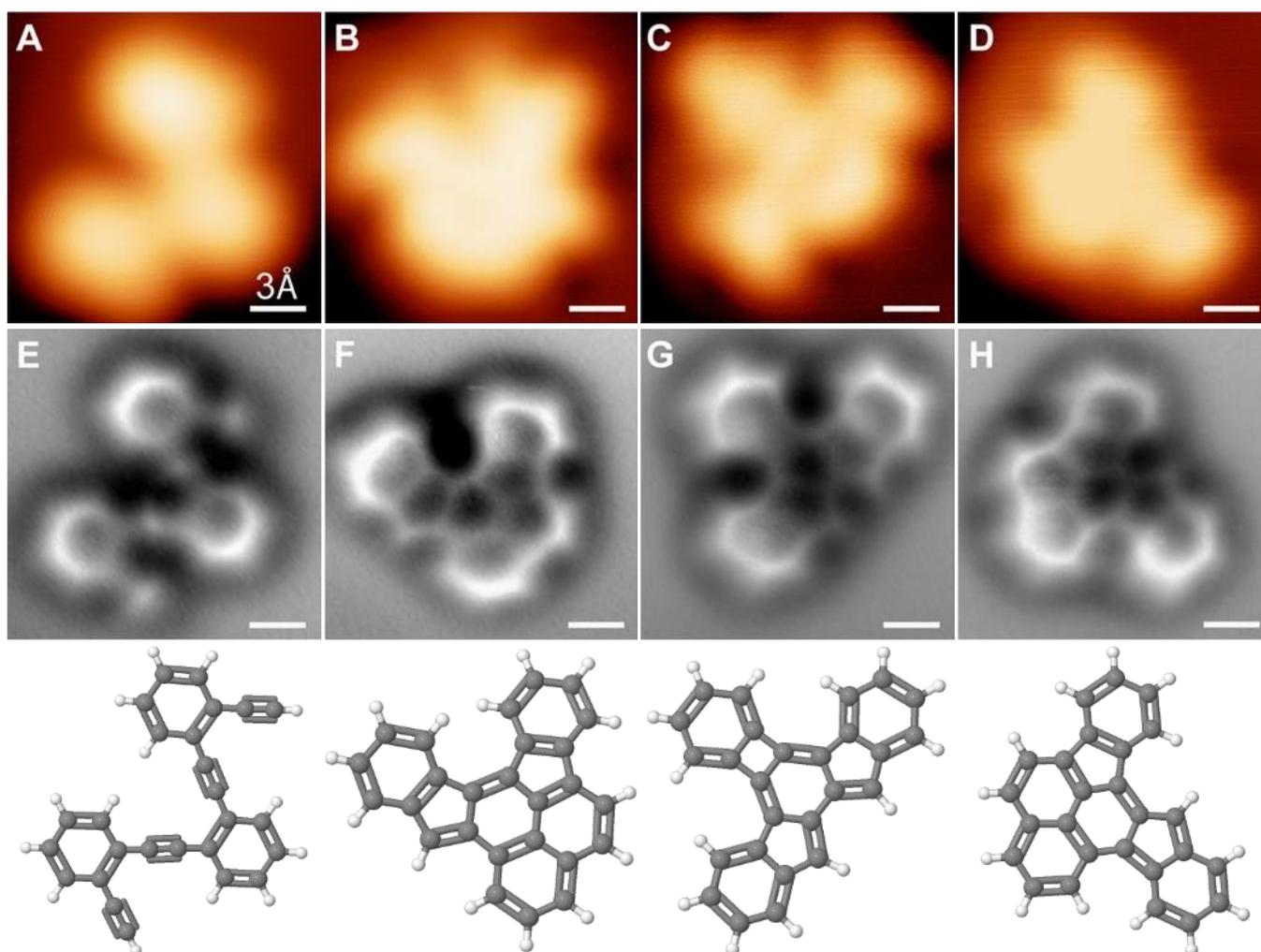


Figure 1. Comparison of STM images, nc-AFM images, and 3D molecular structures model [30]

Representations of formal molecular shapes and surfaces provide more detailed and more chemically relevant information than simple molecular graphs and stereochemical bond structures and give a more faithful description of actual molecular recognition and interaction processes, which lead to the quantitative shape-activity relations (QShAR) domain [38]. Shape is an important visual feature and it is one of the basic features used to describe image content [39], and hence, searching for an image by using the shape features gives challenges for many researches, since extracting the features that represent and describe the shape is an arduous task [40], which also hold true in the QShAR domain [38].

In the QShAR domain itself, various molecular shape representation techniques have been proposed [38], [41]. Meanwhile, in pattern recognition problem, there are many shape representations or description techniques have been explored to extract the features from the object. One of the most commonly used shape descriptors is Moment Invariants (MI), which can easily satisfy the invariance requirements. MI is a special case of Moments, which is a scalar quantities used to characterize a function and to capture its crucial features [42]. The first application of MI to represent molecular structure is 3D Zernike descriptors [43]. Although it was introduced to represent the molecular surface of protein structure, it provides an adequate motivation for further exploration of engaging MI as a numerical representation of molecule in the computer system, whether it is for molecular structure or for molecular surface.

There are several advantages of 3D MI-based molecular shape representation compared to conventional representations. First, 3D MI-based molecular descriptors allow for fast retrieval and comparison of molecular structures. Second, due to its rotation and translation invariance properties, molecular structures need not be aligned for comparison. Lastly, the resolution of the description of molecular structures can be easily and naturally adjusted by changing the order of shape descriptors [43], [44].

Prior of the construction of these 3D MI-based molecular descriptors, it is necessary to prepare a standardized image format as an input for these techniques, which will be discussed in this paper. Thus, the remainder of the paper is organized as follows. The ensuing section will provide an overview of ATS drug identification and analysis domain. In Section 3, the proposed dataset preparation method is presented, while the conclusion and future works are discussed in Section 4.

II. ATS Drug Identification and Analysis

ATS are a group of substances, mostly synthetic in origin, that are structurally derived from β -phenethylamine, as shown in Figure 2, portraying its essential features: aromatic phenyl ring, carbonyl side-chain and amino moiety [2]. Structural modifications of β -PEA create multiple synthetic derivatives known as ring substitute analogues. The substitution positions on the carbonyl side-chain (R1-R4) and aromatic phenyl ring (R5-R9) are shown in Figure 3.

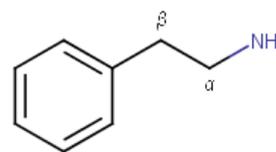


Figure 2. 2D molecular structure of β -phenethylamine [2]

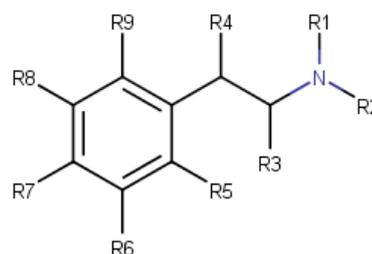


Figure 3. Basic 2D molecular structure of ATS [2]

Chemical modification at the positions R1 to R9 results in a practically unlimited number of pharmacologically active compounds, some of which are more potent stimulants than others. Although there are several possibilities for carbonyl side-chain modification, substitution on the aromatic phenyl ring contributes the most to substantial qualitative differences in pharmacological effects [2].

Based on its structural characteristics, there are three major sub-groups of ATS, which essentially correspond to the following substitution patterns on the aromatic ring: no substitution, methylenedioxy-substitution, and other substitution patterns, usually including one or more alkyloxy group. The substitution patterns are depicted in Figure 4, and some of the notorious examples of ATS drugs are shown in Figure 5.

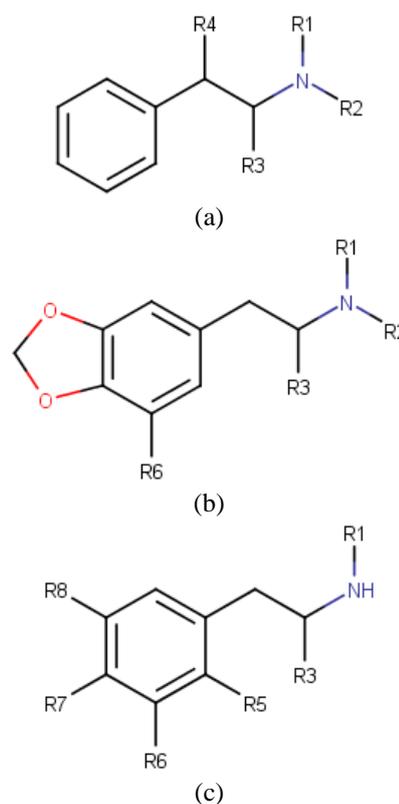


Figure 4. Sub-groups of ATS per substitution patterns: (a) no substitution, (b) methylenedioxy-substitution, and (c) other substitution patterns [2]

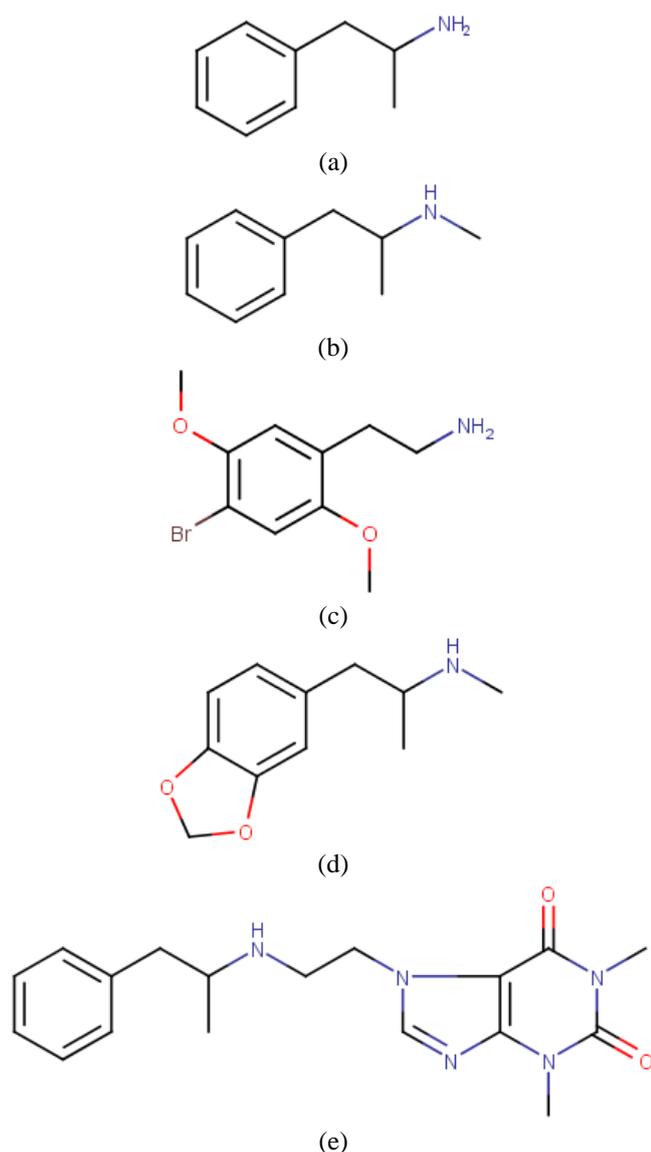


Figure 5. Samples of ATS drug molecular structure: (a) amphetamine, (b) methamphetamine, (c) 2C-B, (d) MDMA, and (e) fenethylamine [2]

To facilitate faster, more accurate and more specific methods for varying ATS drugs identification and analysis, Laboratory and Scientific Section of UNODC has established recommended methods of testing for national drug testing laboratories. However, different results are possibly obtained from different testing laboratory because of their non-conformance to these standards. Nevertheless, most of these laboratories agree to use gas chromatography/mass spectrometry (GC/MS) as the most common method to identify a chemical substance [2], [45], [46]. The flaws of GC/MS which are surfacing while trying to identify several ATS drugs are recently discovered in a study, most notably in identifying methamphetamine [47].

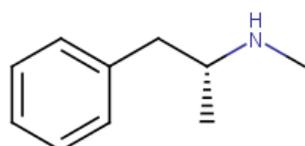


Figure 6. 2D molecular structures of *l*-methamphetamine [48]

Methamphetamine itself has two stereo-isomers, which are *l*-methamphetamine and *d*-methamphetamine. The 2D molecular structure of *d*-methamphetamine is shown in Figure 5(b), while 2D molecular structure of *l*-methamphetamine is depicted in Figure 6. Isomers are defined by [49] as one of several species (or molecular entities) that have the same atomic composition but different line or stereo-chemical formulae and hence different physical and/or chemical properties. GC/MS is also increasingly incapable to determine that several molecular structures are ATS drugs. While *l*-methamphetamine has very little pharmacodynamics effect, *d*-methamphetamine on the other hand is a controlled substance that has high potential for abuse and addiction [48].

Based on the molecular structures shown in Figures 5(b) and 6, there are very minor differences between *d*-methamphetamine and *l*-methamphetamine. The differences on the atom orientation only become apparent if the structure is represented using 3D model of molecular structure. Therefore, this paper believes that the shape of 3D molecular structure can be used to identify the molecular compounds, especially ATS drugs, due to the presence of aromatic phenyl ring and carbonyl side chains which gives its unique characteristics in all ATS analogues [2], [50], [51], which theoretically can be obtained using recent molecular microscopy imaging devices, such as nc-AFM. The example of 3D molecular structure for *d*-methamphetamine and *l*-methamphetamine are depicted in Figure 7.

Although nc-AFM can show the 3D conformation of a molecular compound, it is still in early development stage and requires further improvements before it has real life applications, especially in forensic domain [30]–[33], [52]. Furthermore, since nc-AFM is only surface probe, probing must be conducted several times so that molecules can be captured from multiple angles, and processed afterward using 3D object reconstruction algorithm before it can be recognized in a computer system [53], [54].

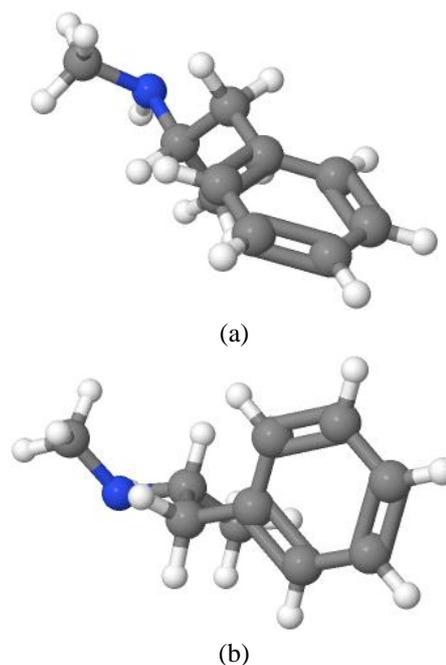


Figure 7. 3D molecular structure of (a) *d*-methamphetamine and (b) *l*-methamphetamine

However, since there is currently no repository or database available which provide the imaging results of nc-AFM and the existing model of 3D molecular structure is similar to 3D conformation of molecular compounds [30], this paper alternatively generates the same output file format produced by 3D object reconstruction algorithm, which is binary volume pixel (voxel) grid [55], [56] to simulate the drugs molecular structure construction process obtained using nc-AFM, which will be thoroughly discussed in Section 3.

III. Proposed Dataset Preparation Method

This section describes the process of data collection and transformation of 3D molecular structure of ATS drugs into 3D computational data representations, which has been briefly outlined in [57]. As discussed earlier, 2D images taken from multiple angle from multiple probing can be reconstructed into binary voxel grid, such as by using 3D Recurrent Reconstruction Neural Network (3D-R2N2) [55]. However, since the probing images of ATS molecular structure are not available, this paper proposes the conversion of 2D molecular structure model into binary voxel grid to train the 3D MI-based molecular descriptors should the probing images become available in the future.

The ATS dataset used in this paper comes from pihkal.info [58], which contains 3780 molecular structures for potentially and typically abused ATS drugs. On the other hand, same number of non-ATS molecular structures are obtained from ChemSpider [59]. These structures are drawn in 2D molecular structure format using MarvinSketch 16.11.28 [60]. The molecular structure depicted in Figure 8 and the subsequent figures throughout this paper is an example of ATS molecular structure, MDMA (3,4-methylenedioxy methamphetamine).

After the 2D molecular structure is drawn, the structure is transformed to 3D molecular structure, also by using MarvinSketch. However, before the conversion takes place, the explicit hydrogens must be added to the structure by using 'Structure' > 'Add' > 'Explicit Hydrogens' command. It is then converted by using 'Structure' > 'Clean in 3D' command, and the output is as depicted in Figure 9. The structure is then saved as Molecular Design Limited (MDL) Structure Data File (SDF) format.

Since the objective of this paper is to prepare the dataset for the validation of the 3D MI-based molecular descriptors, the translation, scale, and rotation transformations must also be applied to the drugs molecular structure to simulate the acquisition process using nc-AFM, where the atom location, resolution and camera distance, and angles of rotation for the same molecular structure may differ between each acquisition. To validate the rotation invariance property of the 3D MI-based molecular descriptors, the MDL SDF format are incrementally rotated for 90 degrees in x -, y -, and z -axis.

Although there are 64 possible orientations if a 3D object is rotated 90 degrees incrementally in x -, y -, and z -axis, there are only 24 distinct orientation exist, and thus, for each molecular structure, there will be 24 files for each distinct orientation. The conversion from 2D to 3D molecular structure and the ensuing rotation transformation of these structures are considered successful if the molecular structure can be opened and viewed by using Jmol 14.6.4 [61], as shown in Figures 10 and 11.

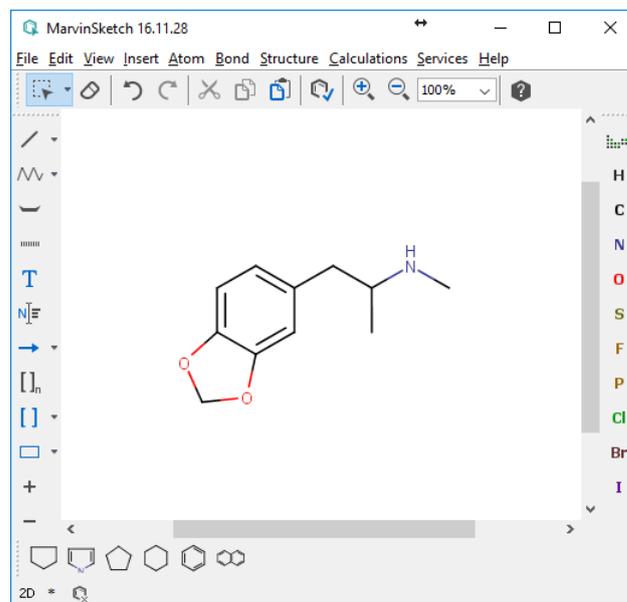


Figure 8. MarvinSketch used to draw 2D molecular structure

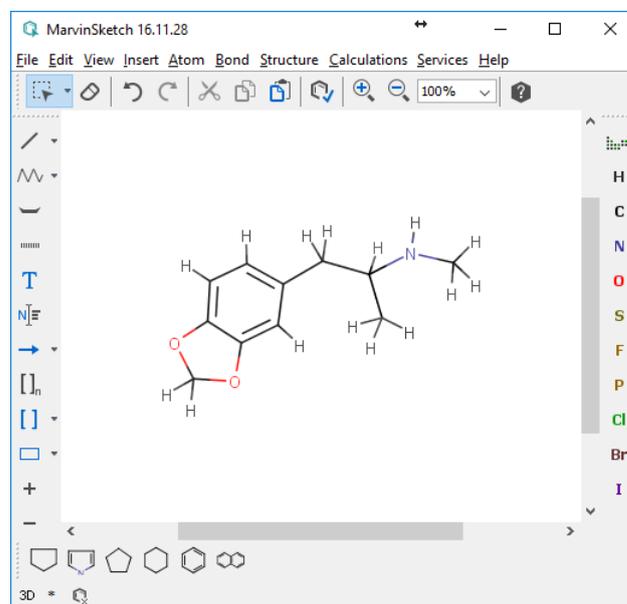


Figure 9. MarvinSketch used for 3D conversion

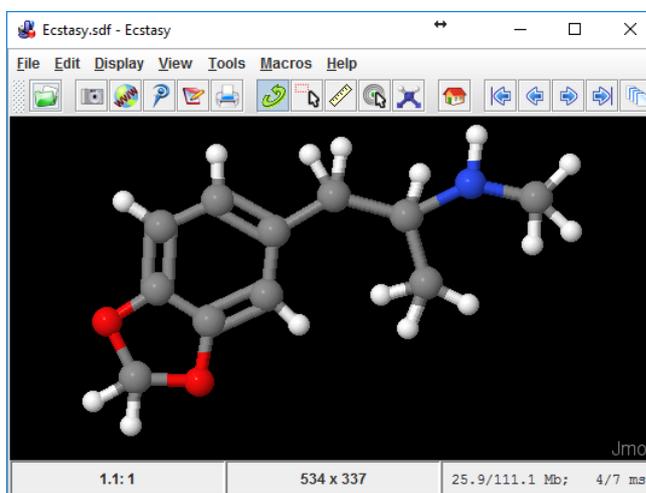


Figure 10. Jmol used for verifying conversion process and converting to VRML file

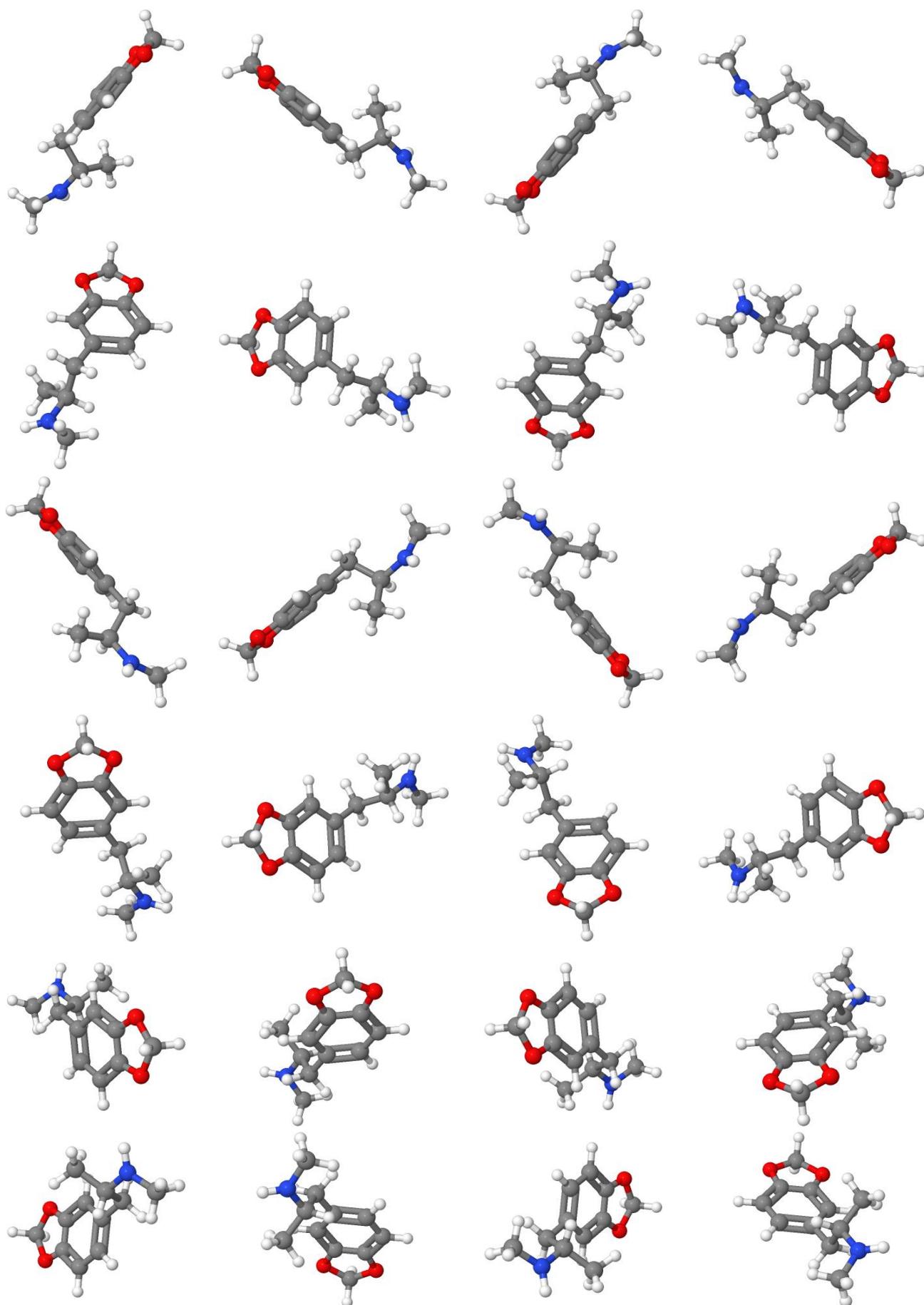


Figure 11. Rotation transformation results

Furthermore, this paper also proposes to construct standardized input format for 3D MI-based molecular descriptors, and thus, the MDL SDF format must be converted to appropriate input file format for the 3D MI-based molecular descriptors, which is binary voxel (BINVOX) grid data. Therefore, the MDL SDF format must be then converted to Virtual Reality Markup Language (VRML) image format. This conversion is required because VRML format is the input type required for generating the BINVOX grid data.

To convert MDL SDF format to VRML file format, Jmol is also used. VRML file is then voxelized into BINVOX grid file using binvox 3D mesh voxelizer 1.22 [62] with randomly selected resolution between $384 \times 384 \times 384$ to 512×512 voxels, as shown in Figure 12, to validate the scale invariance property of the 3D MI-based molecular descriptors. The result of the voxelization process is depicted in Figure 13 by using viewvox 3D voxel model viewer 0.44 [63], and the voxelization result of the original and the scaled and rotated versions of the drugs molecular structure is shown in Figure 14.

The procedure to convert the 3D molecular structure to binary voxel grid is adopting the procedure outlined by [44] and hybridizing it with the procedure outlined by [64], despite different tools are employed in this study. To produce 3D Zernike descriptors, [44] calculates the triangle mesh of Connolly surface from Protein Data Bank (PDB) file, which is a 3D molecular structure format similar to MDL SDF, using MSROLL program in Molecular Surface Package 3.9.3 [65], and then the triangle mesh is placed in a 3D voxel grid. However, the tools used to convert the triangle mesh into 3D voxel grid is not specifically mentioned.

Thus, this study alternatively followed the procedure outlined by [64] to convert VRML file to 3D voxel grid. Although the VRML used in their study comes from Princeton Shape Benchmark, but the tools to convert the VRML to 3D voxel grid is clearly mentioned, which is the binvox 3D mesh voxelizer (older version than the version used in this study). It should be noted that even though [44] and [64] used 3D voxel grid for different purposes, both studies produced 3D voxel grid with $200 \times 200 \times 200$ voxels. However, this study instead produced 3D voxel grid with at least $384 \times 384 \times 384$ voxels for finer detail and resolution.

To further validate the translation invariance property of moment invariants techniques, the BINVOX voxel grid files are also randomly translated by shifting its voxels in one or more directions of x -, y -, and z -axis, ensuring that the 3D image will not be cropped after being translated. The resulting BINVOX grid files are then used as the input for the 3D MI-based molecular descriptors. The summary of the dataset preparation procedure is depicted in Figure 15.

Another point should be noted is that this study focuses on the preparation of input format for 3D MI-based molecular descriptors derived from 3D volumetric moments. As for the techniques derived from 3D surface moments, meshconv 3D model converter 1.26 [66] can be used instead of binvox 3D mesh voxelizer to generate triangular mesh from VRML files as its input format. Additionally, there are also several notable studies which can benefit from the dataset produced in this study, such as studies conducted by [67]–[73].

Figure 12. binvox used to convert VRML to BINVOX format

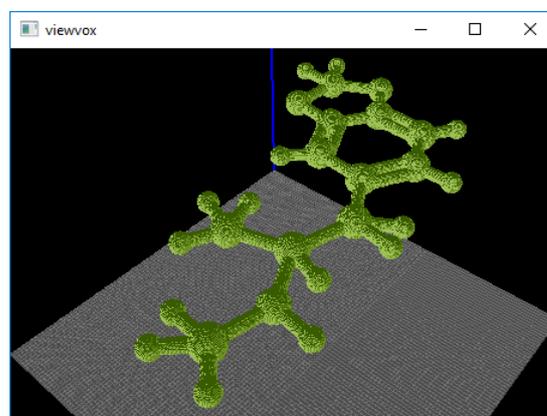


Figure 13. Output of the voxelization process visualized using viewvox

IV. Conclusion and Future Works

This paper proposed a method to construct an input format to be employed for 3D MI-based molecular descriptors, as an alternative input format for the time being, while the recent molecular microscopy imaging devices are being perfected and implemented as a forensic laboratory equipment for the ATS drug identification and analysis. Hence, future works employing the output of this paper as an input for 3D MI-based molecular descriptors should be commissioned, especially on the development of these techniques.

Acknowledgment

This work was supported by UTeM Postgraduate Fellowship (Zamalah) Scheme and PJP High Impact Research Grant (S01473-PJP/2016/FTMK/HI3) from Universiti Teknikal Malaysia Melaka (UTeM), Malaysia. The authors would also like to thank National Poison Center, Malaysia, for validating the formats produced in this paper.

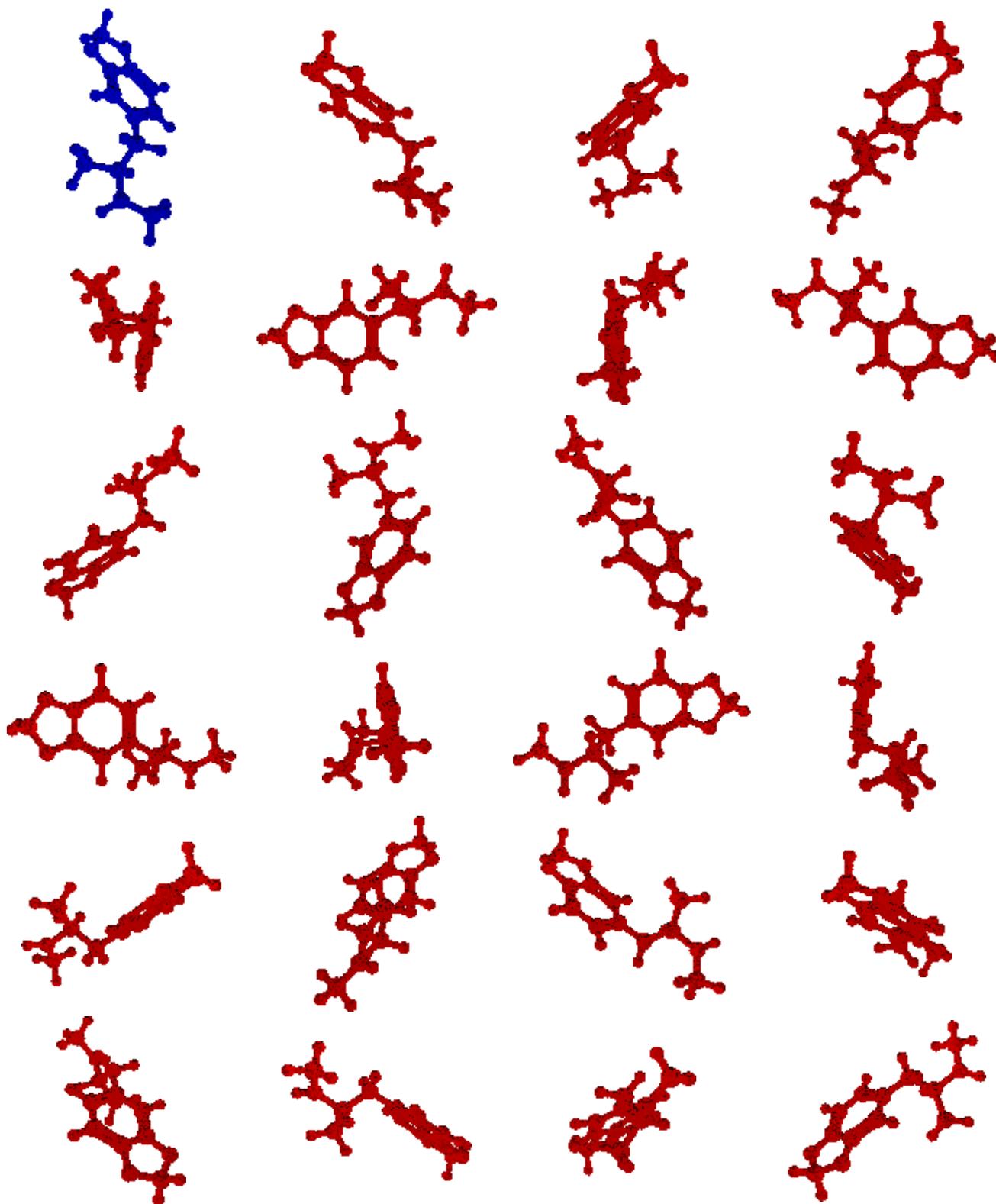


Figure 14. Voxelization result of the original (blue) and the scaled and rotated versions (red) of the drugs molecular structure

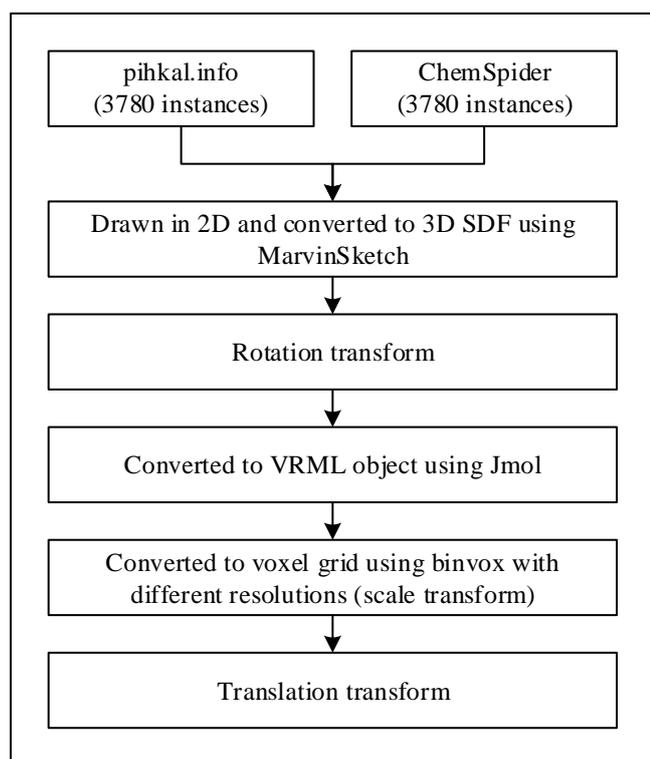


Figure 15. Summary of dataset preparation process

References

- [1] A. Lloyd. "The Analysis of Amphetamine-type Stimulants using Microchip Capillary Electrophoresis". *Dissertation*, University of Technology, 2013.
- [2] United Nations Office of Drugs and Crime: Recommended Methods for the Identification and Analysis of Amphetamine, Methamphetamine and Their Ring-substituted Analogues in Seized Materials. In., vol. Sales No. E.06.XI.1. UNODC, New York, USA, (2006).
- [3] United Nations Office on Drugs and Crime: World Drug Report 2016. In., vol. Sales No. E.16.XI.7. UNODC, Vienna, Austria, (2016).
- [4] Drug Enforcement Administration: Drugs of Abuse: A DEA Resource Guide. In. Drug Enforcement Administration, Springfield, USA, (2015).
- [5] R.P. Bianchi, M.N. Shah, D.H. Rogers, T.J. Mrazik. "Laboratory Analysis of the Conversion of Pseudoephedrine to Methamphetamine From Over-the-Counter Products", *Microgram Journal*, 3(1-2), pp. 11-15, 2005.
- [6] W.S. Cohen. "Ephedra Used as a Precursor in Methamphetamine Manufacturing", *Journal of the clandestine Laboratory Investigating Chemists*, 16(2), pp. 21-22, 2006.
- [7] E. Biavardi, S. Federici, C. Tudisco, D. Menozzi, C. Massera, A. Sottini, G.G. Condorelli, P. Bergese, E. Dalcanale. "Cavitand-grafted silicon microcantilevers as a universal probe for illicit and designer drugs in water", *Angew Chem Int Ed Engl*, 53(35), pp. 9183-9188, 2014.
- [8] P.L. Cary. "Designer Drugs: What Drug Court Practitioners Need To Know", *Drug Court Practitioner Fact Sheet*, IX(2), pp. 1-13, 2014.
- [9] M.J. Swortwood. "Comprehensive Forensic Toxicological Analysis of Designer Drugs". *Dissertation*, Florida International University, 2013.
- [10] M.C.F. Smith. "But what of designer drugs?", *Advances in Psychiatric Treatment*, 17(2), pp. 158-158, 2011.
- [11] S.F. Pratama, L. Pratiwi, A. Abraham, A.K. Muda. "Computational Intelligence in Digital Forensics", in *Computational Intelligence in Digital Forensics: Forensic Investigation and Applications*, Muda, A.K., Choo, Y.-H., Abraham, A., N. Srihari, S. (eds.), Springer International Publishing, Cham, Switzerland, 2014.
- [12] M.D. Krasowski, S. Ekins. "Using cheminformatics to predict cross reactivity of "designer drugs" to their currently available immunoassays", *J Cheminform*, 6(1), p. 22, 2014.
- [13] M.D. Krasowski, A.F. Pizon, M.G. Siam, S. Giannoutsos, M. Iyer, S. Ekins. "Using molecular similarity to highlight the challenges of routine immunoassay-based drug of abuse/toxicology screening in emergency medicine", *BMC Emerg Med*, 9(5), pp. 1-18, 2009.
- [14] M.D. Krasowski, M.G. Siam, M. Iyer, S. Ekins. "Molecular similarity methods for predicting cross-reactivity with therapeutic drug monitoring immunoassays", *Ther Drug Monit*, 31(3), pp. 337-344, 2009.
- [15] M.D. Krasowski, M.G. Siam, M. Iyer, A.F. Pizon, S. Giannoutsos, S. Ekins. "Cheminformatic methods for predicting interference in drug of abuse/toxicology immunoassays", *Clin Chem*, 55(6), pp. 1203-1213, 2009.
- [16] M. Petrie, K.L. Lynch, S. Ekins, J.S. Chang, R.J. Goetz, A.H. Wu, M.D. Krasowski. "Cross-reactivity studies and predictive modeling of "Bath Salts" and other amphetamine-type stimulants with amphetamine screening immunoassays", *Clin Toxicol (Phila)*, 51(2), pp. 83-91, 2013.
- [17] B.D. Gute, S.C. Basak. "Optimal neighbor selection in molecular similarity: comparison of arbitrary versus tailored prediction spaces", *SAR QSAR Environ Res*, 17(1), pp. 37-51, 2006.
- [18] A. Amine, Z. Elberrichi, M. Simonet, A. Rahmouni. "A Hybrid Approach Based on Self-Organizing Neural Networks and the K-Nearest Neighbors Method to Study Molecular Similarity", *International Journal of Chemoinformatics and Chemical Engineering*, 1(1), pp. 75-95, 2011.
- [19] G. Klopmand. "Concepts and applications of molecular similarity, by Mark A. Johnson and Gerald M. Maggiora, eds., John Wiley & Sons, New York, 1990, 393 pp. Price: \$65.00", *Journal of Computational Chemistry*, 13(4), pp. 539-540, 1992.
- [20] D.E. Patterson, R.D. Cramer, A.M. Ferguson, R.D. Clark, L.E. Weinberger. "Neighborhood behavior: a useful concept for validation of "molecular diversity" descriptors", *Journal of medicinal chemistry*, 39(16), pp. 3049-3059, 1996.
- [21] Y.C. Martin, J.L. Kofron, L.M. Traphagen. "Do structurally similar molecules have similar biological activity?", *Journal of medicinal chemistry*, 45(19), pp. 4350-4358, 2002.
- [22] A. Bender, R.C. Glen. "Molecular similarity: a key technique in molecular informatics", *Org Biomol Chem*, 2(22), pp. 3204-3218, 2004.
- [23] P. Willett, J.M. Barnard, G.M. Downs. "Chemical Similarity Searching", *Journal of Chemical Information and Computer Sciences*, 38(6), pp. 983-996, 1998.

- [24] A. Bender. "Studies on Molecular Similarity". *Dissertation*, University of Cambridge, 2005.
- [25] V. Consonni, R. Todeschini. "Molecular Descriptors", in *Recent Advances in QSAR Studies: Methods and Applications*, Puzyn, T., Leszczynski, J., Cronin, T.M. (eds.), Springer Netherlands, Dordrecht, Netherlands, 2010.
- [26] J. Gasteiger, T. Engel. *Cheminformatics: A Textbook*, Wiley-VCH Verlag, Weinheim, Germany, 2003.
- [27] A. Axenopoulos, P. Daras, G. Papadopoulos, E.N. Houstis. "A shape descriptor for fast complementarity matching in molecular docking", *IEEE/ACM Trans Comput Biol Bioinform*, 8(6), pp. 1441-1457, 2011.
- [28] E. Estrada. "Generalized Graph Matrix, Graph Geometry, Quantum Chemistry, and Optimal Description of Physicochemical Properties", *The Journal of Physical Chemistry A*, 107(38), pp. 7482-7489, 2003.
- [29] S. Kortagere, M.D. Krasowski, S. Ekins. "The importance of discerning shape in molecular pharmacology", *Trends Pharmacol Sci*, 30(3), pp. 138-147, 2009.
- [30] D.G. de Oteyza, P. Gorman, Y.C. Chen, S. Wickenburg, A. Riss, D.J. Mowbray, G. Etkin, Z. Pedramrazi, H.Z. Tsai, A. Rubio, M.F. Crommie, F.R. Fischer. "Direct imaging of covalent bond structure in single-molecule chemical reactions", *Science*, 340(6139), pp. 1434-1437, 2013.
- [31] L. Gross, F. Mohn, N. Moll, P. Liljeroth, G. Meyer. "The chemical structure of a molecule resolved by atomic force microscopy", *Science*, 325(5944), pp. 1110-1114, 2009.
- [32] L. Gross, F. Mohn, N. Moll, G. Meyer, R. Ebel, W.M. Abdel-Mageed, M. Jaspars. "Organic structure determination using atomic-resolution scanning probe microscopy", *Nat Chem*, 2(10), pp. 821-825, 2010.
- [33] L. Gross, F. Mohn, N. Moll, B. Schuler, A. Criado, E. Guitian, D. Pena, A. Gourdon, G. Meyer. "Bond-order discrimination by atomic force microscopy", *Science*, 337(6100), pp. 1326-1329, 2012.
- [34] K.O. Hanssen, B. Schuler, A.J. Williams, T.B. Demissie, E. Hansen, J.H. Andersen, J. Svenson, K. Blinov, M. Repisky, F. Mohn, G. Meyer, J.S. Svendsen, K. Ruud, M. Elyashberg, L. Gross, M. Jaspars, J. Isaksson. "A combined atomic force microscopy and computational approach for the structural elucidation of breifussin A and B: highly modified halogenated dipeptides from *Thuiaria breifussi*", *Angew Chem Int Ed Engl*, 51(49), pp. 12238-12241, 2012.
- [35] N. Pavliček, B. Fleury, M. Neu, J. Niedenführ, C. Herranz-Lancho, M. Ruben, J. Repp. "Atomic Force Microscopy Reveals Bistable Configurations of Dibenzo[a,h]thianthrene and their Interconversion Pathway", *Physical Review Letters*, 108(8), pp. 1-5, 2012.
- [36] V. Consonni, R. Todeschini. "Basic Requirements for Valid Molecular Descriptors". http://www.moleculardescriptors.eu/tutorials/T3_moleculardescriptors_requirements.pdf, 2006. Accessed 28 January 2016.
- [37] M. Randić. "Molecular bonding profiles", *Journal of Mathematical Chemistry*, 19(3), pp. 375-392, 1996.
- [38] P.G. Mezey. "Shape-Similarity Measures for Molecular Bodies: A Three-Dimensional Topological Approach to Quantitative Shape-Activity Relations", *Journal of Chemical Information and Computer Sciences*, 32(6), pp. 650-656, 1992.
- [39] D. Zhang, G. Lu. "Shape-based Image Retrieval using Generic Fourier Descriptor", *Signal Processing: Image Communication*, 17(10), pp. 825-848, 2002.
- [40] A.K. Muda. "Authorship Invarianceness for Writer Identification Using Invariant Discretization and Modified Immune Classifier". *Dissertation*, Universiti Teknologi Malaysia, 2009.
- [41] P.G. Mezey. "Theorems on Molecular Shape-Similarity Descriptors: External T-Plasters and Interior T-Aggregates", *Journal of Chemical Information and Computer Sciences*, 36(6), pp. 1076-1081, 1996.
- [42] Y. Sun, W. Liu, Y. Wang. "United Moment Invariants for Shape Discrimination". In: *International Conference on Robotics, Intelligent Systems and Signal Processing*, pp. 88-93, 2003.
- [43] D. Kihara, L. Sael, R. Chikhi, J. Esquivel-Rodriguez. "Molecular Surface Representation Using 3D Zernike Descriptors for Protein Shape Comparison and Docking", *Current Protein and Peptide Science*, 12(6), pp. 520-530, 2011.
- [44] L. Sael, B. Li, D. La, Y. Fang, K. Ramani, R. Rustamov, D. Kihara. "Fast protein tertiary structure retrieval based on global surface shape similarity", *Proteins*, 72(4), pp. 1259-1273, 2008.
- [45] L.J. Langman, L.D. Bowers, J.A. Collins, C.A. Hammett-Stabler, M.A. LeBeau. *Gas Chromatography/Mass Spectrometry Confirmation of Drugs; Approved Guidelines - Second Edition*. In: *Clinical and Laboratory Standards Institute*, Pennsylvania, USA, (2010).
- [46] D.-L. Lin, R.-M. Yin, L.H. Ray. "Gas Chromatography-Mass Spectrometry (GC-MS) Analysis of Amphetamine, Methamphetamine, 3,4-Methylenedioxyamphetamine and 3,4-Methylenedioxymethamphetamine in Human Hair and Hair Sections", *Journal of Food and Drug Analysis*, 13(3), pp. 193-200, 2005.
- [47] J.J. McShane. "GC-MS is Not Perfect: The Case Study of Methamphetamine". <http://www.thetruthaboutforensicscience.com/gc-ms-is-not-perfect-the-case-study-of-methamphetamine/>, 2011. Accessed 13 March 2012.
- [48] J. Mendelson, N. Uemura, D. Harris, R.P. Nath, E. Fernandez, P. Jacob, 3rd, E.T. Everhart, R.T. Jones. "Human pharmacology of the methamphetamine stereoisomers", *Clin Pharmacol Ther*, 80(4), pp. 403-420, 2006.
- [49] International Union of Pure and Applied Chemistry. *Compendium of Chemical Terminology*, Blackwell Scientific Publications, Oxford, UK, 2006.
- [50] S.A. Rahman, M. Bashton, G.L. Holliday, R. Schrader, J.M. Thornton. "Small Molecule Subgraph Detector (SMSD) toolkit", *J Cheminform*, 1(1), p. 12, 2009.
- [51] N. Nikolova, J. Jaworska. "Approaches to Measure Chemical Similarity - a Review", *QSAR & Combinatorial Science*, 22(9-10), pp. 1006-1026, 2003.
- [52] S. Morita. "Introduction", in *Noncontact Atomic Force Microscopy: Volume 3*, Morita, S., Giessibl, F.J., Meyer, E., Wiesendanger, R. (eds.), Springer International Publishing, Cham, Switzerland, 2015.

- [53] Y. Ma, S. Soatto, J. Košecká, S.S. Sastry. "Step-by-Step Building of a 3-D Model from Images", in *An Invitation to 3-D Vision: From Images to Geometric Models*, Ma, Y., Soatto, S., Košecká, J., Sastry, S.S. (eds.), Springer New York, New York, USA, 2004.
- [54] R. Hartley, A. Zisserman. *Multiple View Geometry in Computer Vision*, Cambridge University Press, New York, USA, 2003.
- [55] C.B. Choy, D. Xu, J. Gwak, K. Chen, S. Savarese. "3D-R2N2: A Unified Approach for Single and Multi-view 3D Object Reconstruction". In: *Computer Vision – ECCV 2016: Proceedings of 14th European Conference, Part VIII*, pp. 628-644, 2016.
- [56] A. Kar, S. Tulsiani, J. Carreira, J. Malik. "Category-specific object reconstruction from a single image". In: *2015 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, pp. 1966-1974, 2015.
- [57] S.F. Pratama, A.K. Muda, Y.-H. Choo, A. Abraham. "Preparation of ATS Drugs 3D Molecular Structure for 3D Moment Invariants-based Molecular Descriptors", in *Hybrid Intelligent Systems*, Abraham, A., Muhuri, P.K., Muda, A.K., Gandhi, N. (eds.), Springer International Publishing, Cham, Switzerland, 2018.
- [58] Isomer Design. "pihkal.info". <http://isomerdesign.com/PiHKAL/>, 2015. Accessed 23 January 2016.
- [59] Royal Society of Chemistry. "ChemSpider Database". <http://www.chemspider.com/>, 2015. Accessed 23 January 2016.
- [60] ChemAxon Ltd. "Marvin". <http://www.chemaxon.com>, 2016. Accessed 30 November 2016.
- [61] Jmol. "Jmol: an open-source Java viewer for chemical structures in 3D". <http://www.jmol.org/>, 2016. Accessed 30 November 2016.
- [62] P. Min. "binvox 3D mesh voxelizer". <http://www.patrickmin.com/binvox>, 2016. Accessed 30 November 2016.
- [63] P. Min. "viewvox 3D voxel model viewer". <http://www.patrickmin.com/viewvox>, 2016. Accessed 30 November 2016.
- [64] B. Yang, J. Flusser, T. Suk. "3D rotation invariants of Gaussian-Hermite moments", *Pattern Recognition Letters*, 54, pp. 18-26, 2015.
- [65] M.L. Connolly. "Solvent-accessible surfaces of proteins and nucleic acids", *Science*, 221(4612), pp. 709-713, 1983.
- [66] P. Min. "meshconv 3D model converter". <http://www.patrickmin.com/meshconv>, 2017. Accessed 9 November 2017.
- [67] S.F. Pratama, A.K. Muda, Y.-H. Choo, R. Carbó-Dorca, A. Abraham. "Using 3D Hahn Moments as A Computational Representation of ATS Drugs Molecular Structure", *International Journal on Advanced Science, Engineering and Information Technology*, accepted, 2018.
- [68] S.F. Pratama, A.K. Muda, Y.-H. Choo, A. Abraham. "3D Geometric Moment Invariants for ATS Drugs Identification: A More Precise Approximation", in *Proceedings of the 16th International Conference on Hybrid Intelligent Systems (HIS 2016)*, Abraham, A., Haqiq, A., Alimi, A.M., Mezzour, G., Rokbani, N., Muda, A.K. (eds.), Springer International Publishing, Cham, Switzerland, 2017.
- [69] S.F. Pratama, A.K. Muda, Y.-H. Choo, J. Flusser, A. Abraham. "ATS drugs molecular structure representation using refined 3D geometric moment invariants", *Journal of Mathematical Chemistry*, 55(10), pp. 1951-1963, 2017.
- [70] S.A. Bero, A.K. Muda, C. Yun-Huoy, N.A. Muda, S.F. Pratama. "Similarity Measure for Molecular Structure: A Brief Review", *Journal of Physics: Conference Series*, 892, pp. 1-8, 2017.
- [71] S.F. Pratama, N.A. Muda, F. Salim. "Representing ATS Drugs Molecular Structure Using 3D Orthogonal Fourier-Mellin Moments", *International Journal of Computer Information Systems and Industrial Management Applications*, 9, pp. 135-144, 2017.
- [72] S.F. Pratama, A.K. Muda, Y.-H. Choo, A. Abraham. "Exact Computation of 3D Geometric Moment Invariants for ATS Drugs Identification", in *Innovations in Bio-Inspired Computing and Applications*, Snášel, V., Abraham, A., Krömer, P., Pant, M., Muda, A.K. (eds.), Springer International Publishing, Cham, Switzerland, 2016.
- [73] S.A. Bero, A.K. Muda, C. Yun-Huoy, N.A. Muda, S.F. Pratama. "Rotation Analysis of Moment Invariant for 2D and 3D Shape Representation for Molecular Structure of ATS Drugs". In: *Fourth World Congress on Information and Communication Technologies (WICT)*, pp. 308-313, 2014.