Modern Environmental Science and Engineering (ISSN 2333-2581)
July 2022, Volume 8, No. 7, pp. 398-404
Doi: 10.15341/mese(2333-2581)/07.08.2022/005
Academic Star Publishing Company, 2022
www.academicstar.us

Methodology Development for Identification and Prevention of Illegal Transfer of Major Nuclear Fuel Cycle Items

Chansuh Lee, and Hansol Ko

Korea Institute of Nuclear Nonproliferation and Control (KINAC), Daejeon, 34101, Republic of Korea

Abstract: The recent Russian invasion of Ukraine is a clear indication of a dilemma of economy and security. With national interest and protection as the top priority, the global community is divided into blocks, changing the existing international order. These changes are also affecting export control. Today, export control should be implemented even more cautiously since the internal and external environments are drastically changing, including such events as the trade war against the US, nuclear tests by North Korea, and the war in Ukraine. In the past, the Eastern European countries that were liberated by the collapse of the USSR decommissioned the nuclear fuel cycle and its related facilities. However, illicit trafficking of nuclear material and key equipment to nearby countries of the USSR increased due to a lack of management during the decommissioning, leading to nuclear proliferation. In alignment with these environmental changes, a methodology with the latest techniques incorporated was developed in order to identify and/or prevent the illegal export of key items of the nuclear fuel cycle to neighboring countries. Through this method, effective export control can be expected, which can complement the lack of workforce and resources.

Key words: export control, nuclear major items, x-ray images, machine learning

1. Introduction

The recent Russian invasion of Ukraine clearly shows the dilemma of economy and security. The invasion has shifted globalization. Under the dollar-based US economy, each nation distributed resources efficiently based on a division of labor. Since the invasion, however, the world has been divided into blocks centering on like-minded countries based on their national interest rather than efficiency. With such changes, the existing international order is being transformed, affecting export control.

UNSCR-1504 provided a legal basis for domestic laws of UN member states to regulate WMD-related transfers. Most member states are implementing export controls by reflecting a multilateral export control system, including the guidelines and export control items of the Wassenaar Arrangement, Missile Technology Control Regime, Nuclear Suppliers Group, and Australia Group, according to their domestic laws. The Republic of Korea is also fully implementing export control in response to this movement by the international community.

To ensure free trade and seamless introduction of state-of-art technologies, it is important to comply with international norms, and adopting strategic trade control has a positive impact on the economy [1]. The ROK, with its high dependency on foreign markets, is faithfully implementing international norms on export control by joining the Non-Proliferation Treaty (NPT) and signing key agreements for non-proliferation such as the IAEA-ROK Safeguards Agreement, and by becoming a member of all international systems for export control.

Corresponding author: Chansuh Lee, Master, research areas: nuclear nonproliferation, export control, nuclear policy. E-mail: chans@kinac.re.kr.

Despite the ROK's rising reputation for nuclear power and growing influence in the international community, the country lacks experience in export control regulations or evaluation criteria for major items or parts in sensitive areas of the nuclear fuel cycle, except for nuclear reactors. As regulation items and levels differ from country to country, it is necessary to develop the ROK's proprietary regulation system to align with technological advancements and the changing external environment. Furthermore, since regulation requires an extensive workforce and resources, automated and advanced technologies are essential to generate maximum output with limited resources. To this end, this study aimed to develop a methodology to identify strategic goods based on Supervised Machine Learning and Data Augmentation.

To develop an algorithm to identify and prevent illicit trafficking, three stages of the study were conducted, from building a database of the major nuclear fuel cycle items and modelling, to making X-ray images, and to image-based algorithm development. This study examined the critical equipment managed by the IAEA, excluding nuclear material. The research process for the prevention of illicit trafficking of these major nuclear fuel cycle items is shown in the figure below (Fig. 1).

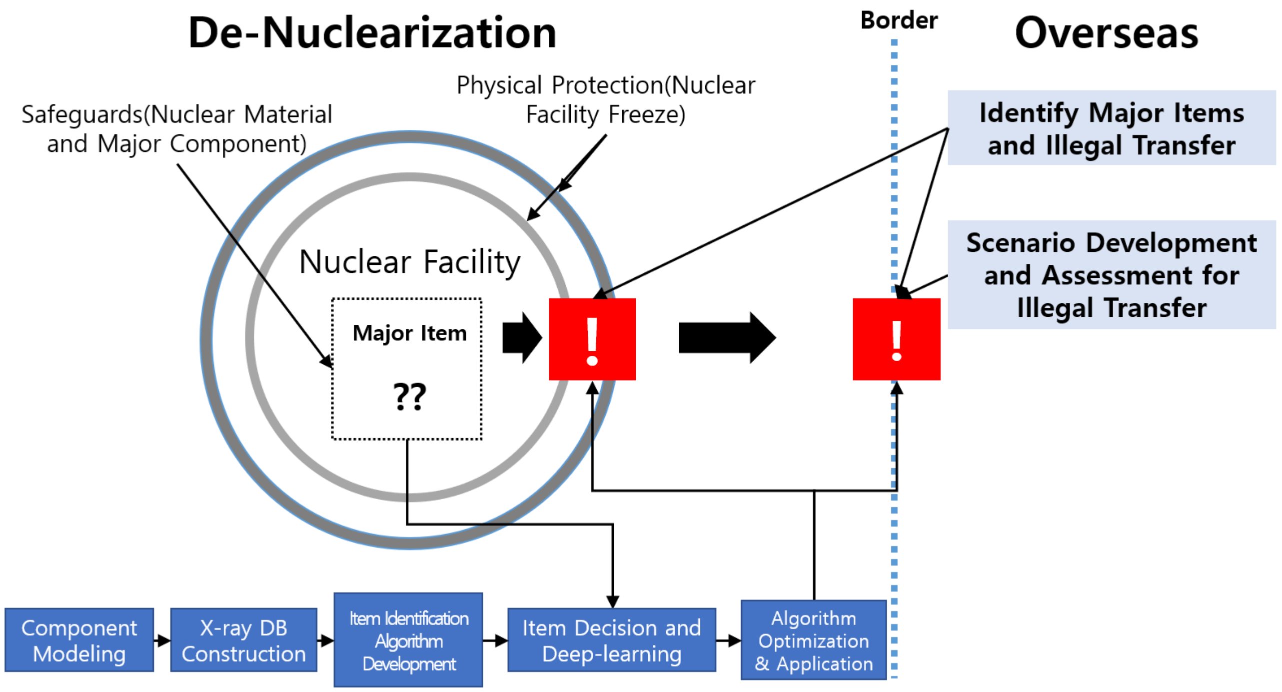

Fig. 1 Process for preventing illegal transfer of nuclear major items.

When denuclearization of nuclear facilities is initiated in neighboring countries, freezing nuclear facilities and accounting of nuclear materials and major equipment are performed. Next, export control should be conducted in cases of transfer or export of nuclear material and major equipment abroad. Since X-ray images for major items are extremely difficult to obtain, major equipment is to be modeled using open-source information and made into a mock-up model. By conducting an X-ray penetration test on the mock-up, an image DB is built and, based on this DB, an algorithm for item identification is developed. In the future, if denuclearization is pushed forward, the proposed algorithm can immediately be used for actual export control by loading real data into the algorithm for learning after target items are determined through evaluation, followed by acquiring drawings and X-ray images of the items.

2. Selection and Model Construction of Major Items for Nuclear Fuel Cycle

The items targeted for export control are those designated by the four international export control systems. These items are those that can contribute to the proliferation of weapons of mass destruction (WMD), and include Trigger List Items used only for nuclear power, Dual-Use Items used for both industry and military use, and Munitions used for military purposes. There are no selection criteria for items, parts, used items, and other items used for the nuclear fuel cycle except for the above basic control items. Criteria may differ by country, but there are watch-list items that are not strategic items but are subject to control depending on the situation and require attention. The US, France, and the UK use the watch lists; however, the item selection criteria have not been disclosed. Accordingly, the ROK has developed its own methodology for selecting major nuclear fuel cycle items.

Since not all the selected items can be constructed and tested, and very large items of nuclear fuel cycle can be easily identified and are often too big to enter a baggage scanner, the target items were limited to those that can enter or leave in cargo. Because it is nearly impossible to build the major nuclear fuel cycle items at actual size and perform permeation tests on cargo, a smaller-sized model was developed with a scaled-down simulation test, and an X-ray penetration test was conducted on the model. In an effort to match the X-ray images of the model with the X-ray images of the actual items as closely as possible, the penetration test was carried out using the Monte Carlo N-Particle Transfer (MCNP) Code, and a simulation was performed to check if an image can be obtained through a cargo container.

2.1 Selection of Major Items for Nuclear Fuel Cycle

This study applied the Delphi Method [2] and Analytic Hierarchy Process (AHP), which are effective for cases where sufficient records are not available and statistical verification is not possible [3]. To select the target items that affect nuclear proliferation, a comparative analysis was conducted comprehensively on the NSG Handbook [4], the list of essential equipment for safety measures [5], and the crucial items of major nuclear facilities in North Korea [6]. As a result, a total of 271 items were selected in consultation with the experts and persons in charge of export control.

To derive evaluation factors for major items, applications for export control of other countries and applications for export licenses related to weapons of mass destruction were reviewed. By comparing the Department of Energy and the Ministry of Commerce in the US, Germany, the UK, Japan, and ROK and reflecting expert opinions, the final evaluation indices were determined: Item Characteristics, Technology Characteristics, Regulations, and Completeness. Then, a total of 14 evaluation factors were selected, including 6 factors for item characteristics, 2 factors for technology characteristics, 3 factors for regulations, and 3 factors for completeness. To compare the importance of the evaluation indices, the AHP method was adopted, involving 30 nuclear non-proliferation experts in the ROK. It is shown in Fig. 2. Table 2 presents the results of evaluating the AHP technique by paired comparison from layers 1 to 3; the main items obtained are as follows.

Nuclear Reactors: Nuclear Reactors, Reactor Core, Control Rods and Equipment, Nuclear Fuel Cladding, Graphite Reflectors.

Enrichment: Gas Centrifuge, Rotor Assemblies, Centrifuge Housing/Recipients, Scoops.

Conversion: Electrolytic Cells for Fluorine Production, Hydrogen Fluoride Kiln Reactors, Systems for the Conversion of UF6 to UO2 (Reduction Furnaces, Kiln Reactors, Precipitation Vessels, Homogenizers).

Reprocessing: Irradiated Fuel Element Chopping Machines, Dissolvers (Vessels, Coolers), Pulsed Column, Mixer-Settler, Systems for the Conversion of

Plutonium Nitrate to Oxide (Vessels, Filtrations).

Nuclear Fuel Fabrication: Equipment which seals the Nuclear Material within the Cladding (Cladding Pressurizing and Welding Equipment), Pellet Inspection Stations (Pellet Inspection Equipment, Nuclear Fuel Inspection Equipment, Mass Spectrometers), Nuclear Fuel Elements.

Table 1 The number of nuclear major items in nuclear facilities.

	Nuclear Reactor	Uranium Enrichment Facility	Uranium Conversion Facility	Reprocessing Facility	Nuclear Fuel Fabrication Facility	Total
Number of Items	23	88	69	55	36	271

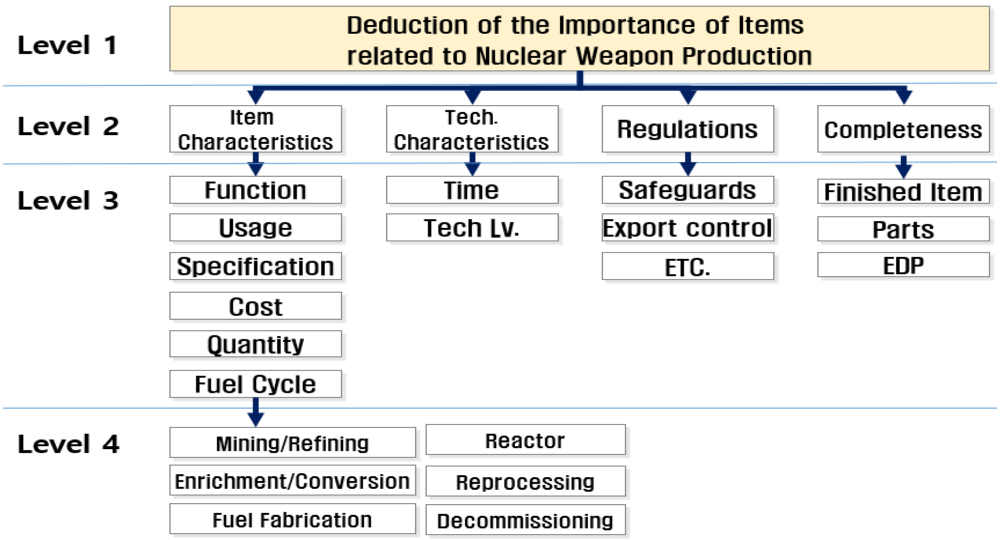

Fig. 2 AHP for deduction of the importance of items related to nuclear weapon production.

Table 2 AHP analysis result of variables.

	Variables	Weight (Rank)	Parameter	Weight (Rank)
1	Item Characteristics	0.2594 (2)	Function	0.2009 (3)
2			Usage	0.2177 (2)
3			Specification	0.1507 (4)
4			Cost	0.1027 (5)
5			Quantity	0.0937 (6)
6			Fuel Cycle	0.2344 (1)
7	Tech. Characteristics	0.2176 (3)	Manufacturing Time	0.3222 (2)
8			Tech Level	0.6778 (1)
9	Regulations	0.3579 (1)	Safeguards	0.3488 (2)
10			Export Control	0.4363 (1)
11			Etc.	0.2149 (3)
12	Completeness	0.1651 (4)	Finished Item	0.4417 (1)
13			Parts	0.2176 (3)
14			Especially Designed or Prepared (EDP) Item	0.3406 (2)

2.2 3D Modeling, Model Construction, and X-ray Image Acquisition

Before building a mock-up model, items that are larger than container size and visible to the naked eye were excluded as most nuclear fuel cycle items used in nuclear power plants are very big, usually longer than several meters. The item for a mock-up model was selected from those that can be contained in a 40ft international standard container cargo (Width 2.438 meters, Height 2.62 meters, Length 12.2 meters) [7]. Before model making, 3D modeling drawings were designed with Autodesk Inventor®, an AutoCAD-based software, using public drawings and collected report images. The metal model was built at a size small enough to pass through a baggage scanner in order to obtain X-ray images from both the baggage scanner and container scanner. SUS304 stainless steel was used as the default material, and some alloys such as aluminum steel were used for constructing models because special steels such as Zirconium steel or Maraging steel are either strategic materials or high in rarity. The ten major nuclear fuel cycle items are Nuclear Fuel Assemblies (IRT2000), Nuclear Fuel Rods (Magnox, PLUS7), Gas Centrifuges (P-2 Type, P-4 Type), Reduction Furnaces, Rotary Kilns, Pulsed-Columns, Mixer-Settlers, Dissolvers, etc.

After models were built, X-ray images of the models were obtained using the HI-SCAN 6040 baggage scanner that generates 140 kilovolts X-rays and the LINASEC SM-06 container cargo scanner that generates six megavolts X-rays. Table 3 shows a comparison between the two scanners. The HI-SCAN scanner produces images using X-rays from an X-ray generator on an object moving through a conveyor belt, whereas the LINASEC scanner obtains images using X-rays generated from a linear accelerator on a fixed object. Also, an example of P-2 Type Gas Centrifuge is shown in Fig. 3.

Table 3 The comparison of x-ray inspection equipment.

	HI-SCAN 6040 CTiX (Smiths Detection, Inc.)	LINASEC SM-06 (SEC, Inc.)
Size of a Tunnel	620 mm (Width)×420 mm (Length)	100 cm (Width)×50 cm (Length)
Energy of X-Ray Source	140 Kilovolts	6 Megavolts
Penetration depth	Max. 31 mm (Steel Alloy)	Max. 3000 mm (Steel Alloy)
Source of X-Ray	X-ray Generator	Linear Accelerator

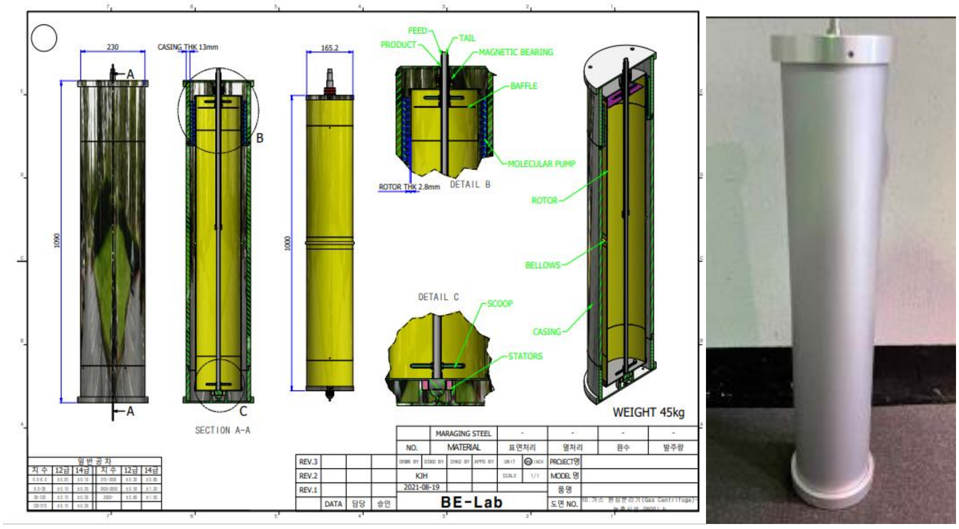

Fig. 3 3D model drawing of gas centrifuge produced by Autodesk Inventor® design application.

3D modelling of a centrifuge was carried out based on the P-2 type gas centrifuge from among the Zippe type centrifuges, and the completed model was built at actual size to allow assembling and disassembling into parts and performing of operations such as bearing operation. The X-ray images obtained using HI-SCAN and LINASEC scanners are shown in Fig. 4. The X-ray images from the HI-SCAN scanner showed distortion as the X-ray penetrated the object moving through the conveyor belt in a short time, while the X-ray images from the LINASEC scanner were only slightly distorted because 2D Computed Tomographic (CT) scan was performed with the object fixed. Further, outlines of items in the X-ray images from the HI-SCAN scanner were well-defined due to the low-energy X-rays. However, the X-ray images from the LINASEC scanner showed rather blurred outlines of items as most of the X-rays were transmitted consistently using high-energy X-rays. The two types of X-ray images obtained were used to select or reprocess the images to fit the identification algorithm.

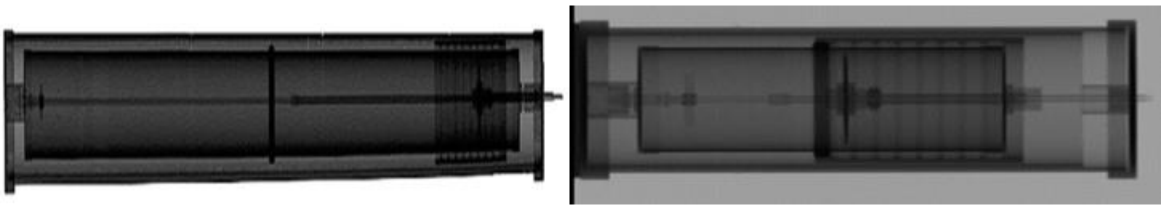

Fig. 4 X-ray images of P-2 type gas centrifuge models by HI-SCAN (Left) and LINASEC inspection equipment (Right).

3. Development of Identification Algorithms for Major Nuclear Fuel Cycle Items

3.1 Previous Studies

With the growing importance of X-ray inspection due to increasing international trade volume and smuggling activities worldwide, more and more X-ray inspections are adopted at customs. Studies on technologies using computer vision are on a gradual rise to address problems caused by human errors and the lack of workforce and resources [8]. A case in point is that of the ROK. The country applied deep learning technology to X-ray images of guns, knives, and explosives in 2020 [9]. Since no actual case was uncovered, researchers created and used a virtual learning set using the Generative Adversarial Network (GAN) [10], a deep learning technology, and produced substantial results. There are also ongoing studies in Switzerland, the UK, Chile, and the EU to bolster inspections at customs.

3.2 Development of Algorithms

At present, to develop AI models, X-ray images of major items are needed but not available. To overcome this hurdle, learning data can be generated with a simple photomontage using random hover, rotation, and CutMix, but the quality may not be satisfactory. Using GAN technology, images similar to actual images of items can be automatically produced, although the level of difficulty may be high and the

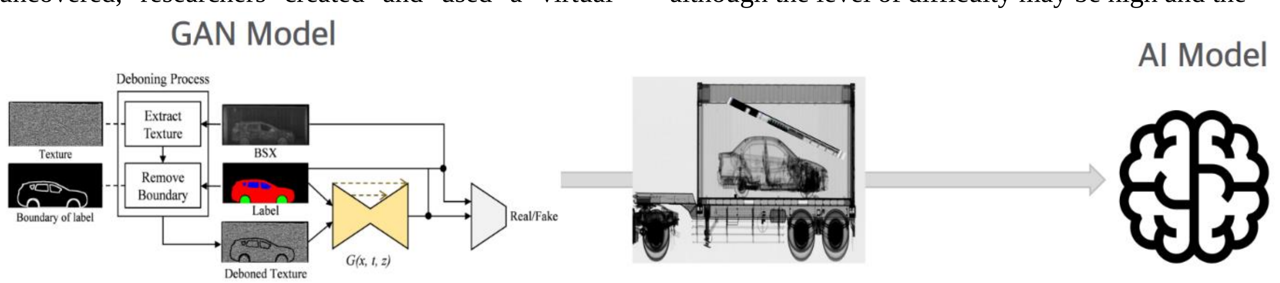

Fig. 5 Data augmentation process of backscatter x-ray images for deep-learning based automatic cargo inspection.

shape of major items may change. This study intends to use a light and practical model, YOLO (You Only Look Once)-v5 [11], that detects major items based on generated learning data in the algorithm development. The light and speedy model is to be expanded after development.

4. Conclusion

With the emergence of various issues associated with trade security, strict compliance with international norms and pursuant domestic industry protection are becoming more imperative than ever. Since transfer volume and smuggling between national borders are rising, item identifying techniques are under development through X-ray image machine learning for efficient inspection. In this study, a methodology was developed to prevent the illegal transfer of major nuclear fuel cycle items and to enhance the ROK's export control capability to prepare for the denuclearization of neighboring countries.

First, a methodology to select major items was established. Then, a simulation was performed through computer codes and by developing modeling methods and models that can be utilized in the absence of actual X-ray images of major items to uncover cases of illicit trafficking. Moreover, since it is challenging for an examiner to inspect all customs clearance items without making a single mistake, an algorithm to identify items is to be developed using deep learning. To date, X-ray images of only ten items have been obtained. Due to the insignificant number of images, image augmentation techniques will be applied to greatly increase learning data. Based on the completed training dataset, algorithms to identify major items are under development. This study is expected to become a foundation for the implementation and execution of effective export control that can protect the trade security and economy of the ROK amid the rapidly changing global environment and complement insufficient workforce and resources.

Acknowledgements

This work was supported by the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KoFONS), using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (No. 2004026).

References

[1] Scott Jones, Johannes Karreth, *Assessing the Economic Impact of Adopting Strategic Trade Controls*, U.S. Department of States, 2010.

[2] M. Turoff, The design of a policy Delphi, *Technol. Forecast. Soc. Change* 2 (1970) 149-171.

[3] T. L. Saaty, *Multicriteria Decision Making*: *The Analytic Hierarchy Process*, Vol. 1, AHP Series (extended edition), RWS Publications, 1990.

[4] DOE NNSA, NSG Part1 handbook for the nuclear suppliers group Trigger List Annexes, 2020.

[5] H. Cooper and T. T. Edwards, *Definition of Essential Equipment for Facility Operation — An Operator's Perspective*, UK Department of Trade and Industry, 2002.

[6] J. H. Park, A study on process standardization in Pu cycle and verification method of process data, KINAC/CR-002/2021, 2021.

[7] ISO668 Freight Containers — Classification, Dimensions and Ratings, 2020.

[8] JLK Inspection, Inc. Final Report of Preliminary research on the implementation of artificial intelligence in the field of X-ray screening for the advancement of customs border management, 2018.

[9] J. W. Lee and T. J. Moon, Modern sphinx: X-ray inspection technology for customs, *Electronics and Telecommunications Trends* 35 (2020) (6) 37-47.

[10] Ian J. Goodfellow, Jean Pouget-Abadie, Mehdi Mirza, Bing Xu, David Warde-Farley, Sherjil Ozair, Aaron Courville and Yoshua Bengio, Generative adversarial nets, in: *Proceedings of the International Conference on Neural Information Processing Systems (NIPS 2014)*, pp. 2672-2680.

[11] J. Solawetz, YOLOv5 New Version — Improvements and Evaluation, 2020.