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Setting the Boundaries of the AI Landscape: An Operational Definition for the European Commission's AI Watch

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Abstract. This work presents an operational definition that facilitates a common understanding of AI and its measurability, paving the way for a transparent and comparable monitoring activity in the context of AI Watch, the European Commission's knowledge service to monitor the development, uptake and impact of artificial intelligence (AI) for Europe. The operational definition is constituted by a taxonomy and a list of related keywords. The method that we propose is iterative, considering that AI is a dynamic field, so its definition should be updated over time to capture the rapid AI evolution. The method consists of the following steps: (i) qualitative analysis of AI definitions and subdomains emanating from reports with academic, industrial and policy perspectives, (ii) selection of definition as starting point, taxonomy formation, and identification of representative keywords in AI with a natural language processing method, and (iii) taxonomy and keywords validation. This results in a unique taxonomy that represents and interconnects all the AI subdomains from political, research and industrial perspective and enables the efficient mapping of the AI landscape of economic agents across different technological areas.

1 INTRODUCTION

Artificial intelligence (AI) has become an area of strategic importance and been identified as a potential key driver of economic development [7][8]. To monitor the development, uptake and impact of AI in Europe within the global landscape, the European Commission launched the AI Watch knowledge service. There are several AI definitions depending on the focus of each work [14][17][33][36][37], while a single generally accepted definition does not exist. The aim of this work is to establish an inclusive operational definition of AI to be adopted in the context of AI Watch for measurement and monitoring purposes. The definition is proposed to be in the form of a concise taxonomy and a set of keywords that represent sufficiently the core and transversal AI domains, and it is expected to overlap with other technological domains. This will assist in the objective of mapping the AI system of interrelated economic agents, and will allow the description of their technological areas of specialisation, which also addresses the need to monitor the implementation of the EC Coordinated Plan on AI on an annual basis [7].

To explore the AI domain's characteristic definitions and subcategories, we consider documents from the policy and institutional, the research and the market perspectives. The consideration of the three perspectives provides a comprehensive overview of the past and current perceptions of AI and the evolution of the concept over time.

AI has been described by certain approaches in relation to human intelligence, or intelligence in general. Many definitions refer to machines that behave like humans or are capable of actions that require intelligence [1][2][10][11][12][18][19][20][21][22][25][26][33][39][41]. Since human intelligence is also difficult to define and measure, and although there have been different attempts of quantification [11][12][24], the objective definition of something subjective and abstract as intelligence results in goal-driven definitions that yet do not propose measurable research concepts [9] [13] [14] [24] [29] [36] [37] [38] [39] [43]. The oversimplification of the concept of intelligence that is needed to define or develop AI is illustrated by Russell and Norvig [33] and emphasised by the High Level Expert Group on Artificial Intelligence (HLEG) [15] by focusing on rational AI, and hence considering benchmark against an ideal performance.

The standard that was published in 1995 to define the basic concept related to AI (ISO/IEC 2382-28:1995), is withdrawn and replaced by the ISO/IEC 2382:2015 [16] that is currently under review. The International Organization for Standardization (ISO) formed two sub committees with six working groups and one study group with the goal to develop 10 AI standards for ISO/IEC (joint technical committee of the International Organisation for Standardization and the International Electrotechnical Commission). Therefore, until May 2020 an updated standardised definition for AI is not included in the published standards.

The High-Level Expert Group (HLEG) on AI has been appointed by the European Commission with the main aim to support the implementation of the European AI Strategy. This includes the elaboration of recommendations on future-related policy developments and on ethical, legal and societal issues related to AI, including socio-economic challenges. One of the first outputs of the HLEG on AI is a definition of AI that describes a common understanding of the domain and its capabilities [15].

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Despite the multiple facets of AI, following the review of existing definitions of AI certain common characteristics can be identified, which can be considered as the main features of AI. These will be presented as part of the results of this work in Section 3. In particular, in the following sections are presented the methodology for the development of the operational AI definition (Section 2), the proposed baseline definition, and the operational definition consisted of a taxonomy and keywords that characterise the AI domain (Section 3), and conclusions of this study (Section 4).

2 METHODOLOGY

To establish an operational AI definition to be adopted in AI Watch, composed by a taxonomy and representative keywords, we propose a 3-layer approach that allows the dynamic update of all the aforementioned. This approach consists of the following layers: 1) review of existing definitions and AI definition selection, 2) taxonomy formation with core and transversal AI subdomains, and 3) pertinent keyword selection for each subdomain of the taxonomy. A more detailed description of the proposed methodological approach and the results on which this work is based, can be found in [35].

2.1 1st layer: AI definition selection

A standard definition of AI is not agreed, despite the increased interest in AI by the academia, industry and public institutions. Hence, the objective of the first layer of the approach is to select a reference definition for AI Watch by reviewing the existing AI definitions. To achieve this, we collect and analyse the existing definitions and identify the main subdomains covering all aspects in the AI field from policy/institutional perspective, research, and market, since the establishment of the first definition in 1955 until today. A number of these documents are mentioned in the introduction, the selection of the definition is explained in §3.1, and the full list of collected documents can be found in [32][35].

2.2 2nd layer: Operational definition - Taxonomy

In the second layer of our approach, the objective is to form an AI taxonomy that includes all political, research and industrial perspectives. This will allow the mapping of R&D and industrial AI related activities performed by economic agents of the AI landscape. Therefore, this taxonomy has to be consisted of a wide range of core AI related scientific subdomains and transversal topics, such as applications of the former, as well as ethical and philosophical considerations. To analyse existing taxonomies and attempts to disentangle the AI knowledge domain, we explored the following sources:

1. the Internet's largest collection of information about AI (aitopics.org) maintained by the Association for the Advancement of Artificial intelligence (AAAI). The website provides a tree-view of the AI-related technologies and covers research, through journals and conferences, AI applications, authors, and sources such as news, tweets, etc.,
2. specialised conferences: we explore certain of the top AI conferences in order to identify submission groups as proxies of the main current in research sub-fields. The following conference submission groups have been considered: AAAI of 2018, International Joint Conferences on Artificial Intelligence of 2009 and 2018 (IJCAI),
3. the documents that were collected during the review of AI definitions, available in [32][35],
4. the taxonomy and keywords developed by the Working Group drafting the Spanish strategy on AI.

The AI domains and subdomains identified from literature are complemented with a bottom-up approach. In this approach we use a natural language processing method (LDA topic model) to identify thematic subdomains in a collection of more than 64 thousand industrial and R&D activities. This resulted in the identification of six thematic subdomains (machine learning, computer vision, natural language processing, connected and automated vehicles, robotics, and AI services), which correspond to subdomains found in literature, and are part of the proposed taxonomy. The taxonomy as a list of core and transversal domains and subdomains, as well as the reasoning of its formation follows in the relevant subsection (vide infra §3.2.1)

2.3 3rd layer: Operational definition - Keywords

In this layer we aim to identify the most representative keywords for each of the domains and subdomains of the AI taxonomy, in order to enable the boundaries of AI activities carried out by economic agents, and allowing the achievement of another objective, namely the analysis of the AI landscape from a techno-economic perspective. The mapping of the global AI landscape is conducted through the techno-economic segments (TES) analytical approach, which is developed to capture technological and non-technological domains that do not correspond to standard classifications, and that are pervasive and cross-sectoral [32][34]. It is conceived as an analytical framework and replicable methodology to analyse and describe the dynamics of specific TES ecosystems, by exploiting different types of factual data including non-official heterogeneous sources. Two parts of the TES approach are used for the selection of keywords in the framework of this work. The first part is regarding the methodology to select the keywords that are employed to query relevant databases for the identification of activities and economic agents relevant to the technology under study, in this case AI (vide infra steps 1 to 3). The other TES part that is used is regarding the most representative terms of the six AI topics resulted from the topic model on a corpus of 64 thousand documents of R&D and industrial activity (step 4).

The comprehensive multi-step process for the formation of the list of keywords, which combines semi-automatic text mining approach, desk research and domain experts' involvement, follows:

1. Identification of top keywords in the research domain: This step includes the:
   - Selection of a seed subset of scientific articles. We search for the term “artificial intelligence” in the title, keywords or abstract of the publication on all articles in Scopus for the years 2005, 2009, and 2017. The consideration of the time dimension allows capturing recently coined terms, terms that are consolidated, and terms that currently are less or not used but that were important in the past.
   - Identification of articles not triggered by the technology term. In order to analyse articles that do not contain the term “artificial intelligence”, in spite of being involved in AI, we take into consideration the journals in which the

articles captured in the previous sub-step are published. 137 specialised journals are considered, while broad topic journals and the ones that are the focus of other scientific fields are ignored. For instance, the journal "Engineering Applications of Artificial Intelligence" would be selected, while "Physics of Life Reviews" would not, even if the latter has published some AI related articles.

- First draft list of keywords: We analyse all the papers found in the previous sub-step for the three aforementioned years and select the 300 most frequent author's keywords per year, from which generic terms are removed.

2. Identification of keywords in the industrial dimension: To cover terms reflecting the recent industrial developments and AI applications, we also take into consideration sources of industrial activity. To that end, we analyse and extract relevant terms from companies' activities descriptions. Since an equivalent to authors' keywords is not available from firms' descriptions, we obtain the most frequent terms (unigrams, bigrams and trigrams) and manually inspect their relevancy in order to incorporate them to the draft list built in step 1.
3. Initial keyword selection: The list of candidate terms, sorted by relevance based on their frequency of occurrence, is sent for review to in-house researchers, to provide a short selection list. In addition, terms are grouped in case of synonymity, of similarity, and of different spelling. The groups are then reduced to a single term per group. Terms appearing in both sub-lists are prioritised.
4. Selection of keywords through topic modelling: We consider the most representative terms from the six AI subdomains identified from topic modelling on a large corpus (64,000 documents) of R&D and industrial activity. The subdomains are identified by applying semantic clustering with the Latent Dirichlet Allocation (LDA) model, a generative hierarchical mixed-membership model for discrete data [3][4][28]. The model returns the most probable topics that best represent the corpus, without the involvement of any expert to avoid unintentional bias. Only the labelling of topics is done semi-automatically. The most relevant keywords of each of the six topics are also considered, and redundancies with terms already included in the list, are removed.
5. Validation by a panel of experts in several AI subdomains: External experts in different AI areas are requested to select keywords, from a list that was already reviewed by an in-house pool of researchers. The advice for improvement targeted the incorporation of domains and related terms not adequately captured by the research and industrial sources analysed so far.
6. Final review and selection of list of keywords per domain: As a consequence of the review in step 5, areas such as Knowledge representation and reasoning or AI ethics and their corresponding related terms are introduced. The final taxonomy is then formed and the final keyword list defined.

Valuable inputs in this process are the terms describing the submission groups in top AI conferences, the term frequencies observed in AITopics, and the terms produced by the Spanish Working Group on AI responsible for the drafting of the Spanish strategy [13].

3 RESULTS AND DISCUSSION

3.1 Selection of AI definition for AI Watch

To achieve the objective of the first layer of our proposed approach, namely to identify a definition of AI to be used as a reference in the framework of AI Watch, and from this to build the operational definition, we analysed 29 AI policy and institutional reports (including standardisation efforts, national strategies, and international organisations reports), 23 relevant research publications, and 3 market reports. These documents cover definitions of AI from the first one in 1955 until today, certain of which are mentioned in the introduction (full list in [32][35]).

From the qualitative analysis, a set of common characteristics in the AI definitions are detected. These characteristics can be considered as the main features of AI and are the following: (i) the perception of the environment including the consideration of the real world complexity [1][5][6][7][8][10][15][23][25][26][30][31][41], (ii) information processing [5][6][8][9][15][17][23][26][30][41], (iii) decision making, including reasoning and learning [1][5][6][7][8][10][15][16][17][25][26][27][30][41], and (iv) the achievement of specific goals, which may be deemed as the ultimate reason of AI systems [1][7][8][10][15][17][25][27][30].

Taking into consideration the features that many of the explored definitions share, as well as this study's aim and objectives, we consider the definition proposed by the HLEG on AI as the starting point for the development of the operational definition. Although it may be considered highly technical for different audiences and objectives, it is a very comprehensive definition which incorporates the aspects of perception, understanding, interpretation, interaction, decision making, adaptation to behaviour and achievement of goals, whereas other definitions do not address them in their entirety. The HLEG definition of AI is: "*Artificial intelligence (AI) systems are software (and possibly also hardware) systems designed by humans that, given a complex goal, act in the physical or digital dimension by perceiving their environment through data acquisition, interpreting the collected structured or unstructured data, reasoning on the knowledge, or processing the information, derived from this data and deciding the best action(s) to take to achieve the given goal. AI systems can either use symbolic rules or learn a numeric model, and they can also adapt their behaviour by analysing how the environment is affected by their previous actions.*"

Considering that the HLEG definition is comprehensive, hence highly technical and detailed, less specialised definitions can be adopted for studies of different objective, such as enterprise surveys.

3.2 AI Watch operational definition

3.2.1 AI Taxonomy

Based on the AI subdomains and transversal topics that were identified in the sources mentioned in §2.2, and the selected AI definition, AI techniques and sub-disciplines can be grouped under two big groups regarding the systems' capabilities: (i) reasoning and decision making, and (ii) learning and perception. The first group of capabilities includes the transformation of data into knowledge, by transforming real world information into something understandable and usable by machines, and making decisions following an organised path of planning, solution searching and optimisation. This group covers the AI subdomains of Knowledge representation and reasoning (usually making use of symbolic rules to represent and infer knowledge) and Planning (including Planning & Scheduling, Searching, and Optimisation). The second group of capabilities involves learning, meaning the extraction of information, and problem solving based on structured or unstructured perceived data (written and oral language, image, sound, etc.), adaptation and reaction to changes, behavioural prediction, etc. This second group covers AI sub-fields related to learning, communication and perception, such as Machine learning, Natural language processing, and Computer vision.

In order to fulfil the AI Watch's objective of monitoring the development, uptake and impact of AI, the HLEG approach is to be complemented to expand the coverage of industrial activities and societal impacts. The taxonomy that we propose is based on the main AI domains identified by the HLEG and it is enhanced by covering the following additional dimensions: a) rational agents, as entities that make decisions and act in relation to its environment, including interaction with other agents, b) research and industrial developments, and other AI applications such as cloud service models offered by service companies to accelerate AI uptake, c) other AI-related aspects not necessarily technological, such as ethical and philosophical issues, namely transparency, explainability, accountability, fairness and safety, AI nature and evolution.

Considering all the aforementioned points, we propose the AI domains and subdomains presented in Table 1 as representative of the AI field in the context of this work. They are divided into core and transversal domains, the former referring to the fundamental goals of AI, the latter not specifically related to a particular academic discipline or area of knowledge, but as issues common to all the core domains. Therefore, the taxonomy is constructed as a reduced list of abstract high level domains and their related subdomains. These are meant to encompass the main theoretical AI branches, as well as AI related non-technological issues.

Table 1. AI domains and subdomains constituting the AI taxonomy

	AI domain	AI subdomain
Core	Reasoning	Knowledge representation
		Automated reasoning
		Common sense reasoning
	Planning	Planning and Scheduling
		Searching
		Optimisation
	Learning	Machine learning
	Communication	Natural language processing
	Perception	Computer vision
		Audio processing
Transversal	Integration and Interaction	Multi-agent systems
		Robotics and Automation
		Connected & Automated Vehicles
	Services	AI Services
	Ethics and Philosophy	AI Ethics
		Philosophy of AI

It is noteworthy that the suggested domains and subdomains are related, and not disjoint, subsets of AI. This ensues from the nature of the AI field that embraces intertwined applications and theoretical advancements, with fuzzy boundaries. It should be noted that the AI Watch taxonomy is not meant to constitute a rigid classification, but a comprehensive collection of areas that represents AI from our three target perspectives: policy, research and industry.

3.2.2 AI Keywords

The keywords that are identified as most relevant within each AI domain comprising the taxonomy are presented in Appendix A, as the lengthy list would undermine the reading flow of the article. This list of keywords is designed to map and model AI activities of several perspectives. The keywords are presented grouped in the broad categories identified in the taxonomy. As explained in detail in §2.3, this keyword list is intended to be dynamically updated according to new technological developments in core and transversal domains, and to agree with alternative proposals.

The rationale for building the list of keywords is to determine, in a practical way, the boundaries of the ecosystem of economic agents active in AI. The list of keywords will be used taking into account additional considerations. For instance, in order to avoid as much as possible the occurrence of false positives, i.e., the incorrect identification as AI of activities that are not AI related. Furthermore, some of the remaining keywords are considered only after conditioning their co-occurrence with some of the core AI terms, which are considered as the non-intrinsic AI keywords[2].

4 CONCLUSIONS

The absence of a formal commonly agreed AI definition required the development of a process to establish a reference AI definition, and its subsequent operationalisation into taxonomy and representative keywords, which can be adopted in the AI Watch framework and used in mapping and monitoring activities. The proposed iterative process includes three perspectives: policy and institutional, research, and market, in order to acquire a comprehensive overview about the AI domain. The AI definition adopted by the High Level Expert Group (HLEG) on AI is used as a baseline definition. It is selected based on the review of 55 relevant documents covering AI policy and institutional reports (including standardisation efforts, national strategies, and international organisations reports), research publications and market reports. An exhaustive list of the collected documents can be found in [32][35]. The proposed operational definition is composed by a concise taxonomy characterising the core domains of the AI research field and transversal topics; and a list of keywords representative of such taxonomy. As AI is a dynamic field, we propose an iterative method that can be updated over time to capture the rapid AI evolution. Additionally, after a consultation from experts, this operational definition will be revised and

[2] Examples of intrinsic-AI terms used as standalone terms to identify activities are: deep learning, face recognition, swarm intelligence and unsupervised learning. Terms that are only used in combination with intrinsic-AI terms include, for instance: accountability, classification, clustering, cognitive system, industrial robot, service robot and social robot, since these non-intrinsic terms could be used in a non-AI context.

eventual improvements will be introduced according to the received feedback.

While the baseline definition will be used as the general AI Watch definition of AI, the operational definition has a more functional use. Both the taxonomy and the list of keywords are essential to identify, map and characterise the worldwide AI landscape, one of the monitoring goals of AI Watch. The keywords are used in the initial phase to capture the relevant AI activities and the economic agents behind them. The main utility of the taxonomy is to classify AI activities, and will assist in the mapping of the AI landscape and the classification of economic agents' areas of specialisation. Different uses of the keyword list are possible. A narrow use of the list, i.e. selecting only intrinsic-AI terms, allows the identification of relevant AI activities, with an expected low proportion of false positives. When the objective is the categorisation of AI-related activities, a more comprehensive list is more suitable, in order to classify activities in their corresponding taxonomy domains.

In conclusion, this approach proposed in this work succeeds in assembling definitions developed between 1955 and 2019, summarising the main features of the concept of AI as reflected in the relevant literature, and developing a replicable process that can provide a dynamic definition and taxonomy of the AI.

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APPENDIX A: MOST RELEVANT KEYWORDS OF AI DOMAINS

AI domain	AI subdomain	Keyword
Reasoning	**Knowledge representation; Automated reasoning; Common sense reasoning**	case-based reasoning causal inference causal models common-sense reasoning expert system fuzzy logic graphical models inductive programming information theory knowledge representation & reasoning latent variable models semantic web uncertainty in artificial intelligence
Planning	**Planning & Scheduling; Searching; Optimisation**	bayesian optimisation constraint satisfaction evolutionary algorithm genetic algorithm gradient descent hierarchical task network metaheuristic optimisation planning graph stochastic optimisation
Learning	**Machine learning**	active learning adaptive learning adversarial machine learning adversarial network anomaly detection artificial neural network automated machine learning automatic classification automatic recognition bagging bayesian modelling boosting classification clustering collaborative filtering content-based filtering convolutional neural network data mining deep learning deep neural network ensemble method feature extraction generative adversarial network generative model multi-task learning neural network pattern recognition probabilistic learning probabilistic model recommender system recurrent neural network recursive neural network reinforcement learning semi-supervised learning statistical learning statistical relational learning supervised learning support vector machine transfer learning unstructured data unsupervised learning
Communication	**Natural language processing**	chatbot computational linguistics conversation model coreference resolution information extraction information retrieval natural language understanding natural language generation machine translation question answering sentiment analysis text classification text mining
Perception	**Computer vision**	action recognition face recognition gesture recognition image processing image retrieval object recognition recognition technology sensor network visual search
	Audio processing	computational auditory scene analysis music information retrieval sound description sound event recognition sound source separation sound synthesis speaker identification speech processing speech recognition speech synthesis
Integration and Interaction	**Multi-agent systems**	agent-based modelling agreement technologies computational economics game theory intelligent agent

AI domain	AI subdomain	Keyword
Services		negotiation algorithm network intelligence q-learning swarm intelligence
	Robotics and Automation	cognitive system control theory human-ai interaction industrial robot robot system service robot social robot
	Connected and Automated vehicles	autonomous driving autonomous system autonomous vehicle self-driving car unmanned vehicle
	AI Services	ai application ai benchmark ai competition ai software toolkit analytics platform big data business intelligence central processing unit computational creativity computational neuroscience data analytics decision analytics decision support distributed computing graphics processing unit intelligence software intelligent control intelligent control system intelligent hardware development intelligent software development intelligent user interface internet of things machine learning framework machine learning library machine learning platform personal assistant platform as a service tensor processing unit virtual environment virtual reality
AI Ethics and Philosophy	**AI Ethics**	accountability explainability fairness privacy safety security transparency
	Philosophy of AI	artificial general intelligence strong artificial intelligence weak artificial intelligence narrow artificial intelligence